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RESEARCH MEMORANDUM

A COMPILATION OF SUMMARIES FROM NACA REPORTS ON

FUELS RESEARCH, 1945-1952

By J. T. DiPiazza

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

August 5, 1953

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TABLE OF CONTENTS

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2956

INTRODUCTION

The NACA has published a large amount of data on the synthesis and analysis of fuels and on their performance in aircraft propulsion systems. Unfortunately, full benefits are not always obtained from work of the past because of the effort and time required to locate old references. In order to minimize these difficulties, a compilation from NACA publications in the field of fuels research from July 1945 through 1952 has been prepared. A summary of each report is included, and the reports are cross-referenced. These summaries often contain enough information to eliminate the need for obtaining the complete report. If the summary does not contain enough information, it should reveal whether or not close examination of the entire report is warranted.

CN-1

Only partial coverage of NACA research on reciprocating-engine fuel is presented in this compilation, inasmuch as reports published before July 1945 are not included. A more complete summary and analysis of the NACA effort in the reciprocating-engine field appears in Report 1026, "NACA Investigation of Fuel Performance in Piston-Type Engines" by Henry C. Barnett. Combustion and fuel research are often closely related; however, only those reports that contain what are considered to be pertinent data on fuels research have been included.

I. RECIPROCATING ENGINE FUEL

A. Antiknock Additives

Knock-Limited Performance of Blends of AN-F-28 Aviation Gasoline Containing 2 Percent Amines - Part V. By Henry Alquist and Leonard K. Tower. NACA WR E-151, 1945. (Supersedes NACA MR E5H06.) 5 pp.; 2 tables; 7 figs.; Unc.

Tests were conducted to determine the effect of 2-percent additions of seven aromatic amines on the knock-limited performance of 28-R fuel in a CFR engine. Knock tests were made of seven aromatic amines synthesized, or purchased and purified, at the Cleveland laboratory of the NACA. The amines tested were N-methyl-p-ethylaniline, N-methyl-o-toluidine, N-methyl-p-isopropylaniline, N-methyl-2,4-xylidine, methyldiphenylamine, N-methyl-ar-ethylaniline (mixture of N-methylethylanilines), and 2,4,6-trimethylaniline. The knock-limited performance of 28-R fuel with and without 2-percent additions of each of these aromatic amines was determined with a modified F-4 engine at three sets of operating conditions. Ratings were also determined for 28-R and all the fuel blends with an F-3 engine. 2956

The results are summarized as follows:

1. The most effective anti-knock additives of the aromatic amines tested were N-methyl-ar-ethylaniline, N-methyl-p-ethylaniline, and N-methyl-p-isopropylaniline.

2. Other aromatic amines which are of interest as anti-knock additives are N-methyl-2,4-xylidine, N-methyl-o-toluidine, and 2,4,6-trimethylaniline.

3. With certain exceptions the addition of a single methyl radical to the nitrogen atom of an aromatic amine increased the knock-limited power and decreased the temperature sensitivity at most fuel-air ratios and engine conditions.

* * *

The Knock-Limited Performance of S Reference Fuel Plus 2 Milliliters of Triethylthallium Per Gallon. By Carl L. Meyer. NACA WR E-112, 1945. (Supersedes NACA RB E5J15.) 3 pp.; 1 table; 1 fig.; Unc.

Published data indicate that the vapors of thallium, when introduced into the combustion chamber of an internal-combustion engine, are effective as an antiknock agent. On a weight basis, the thallium vapors were found to have several times the antiknock value of tetraethyl lead, which was added to the fuel. The amount of thallium vapor necessary to raise the antiknock properties of a gasoline up to exact equivalence with a benzol-gasoline mixture was determined in these engine tests.

In view of the encouraging results for thallium vapors reported, tests of the antiknock effectiveness of a thallium compound, when added to the fuel, were considered advisable.

Knock-limited performance data were obtained in April 1945 in a small-scale single-cylinder engine at two inlet-air temperatures for S-4 reference fuel plus 2 ml triethylthallium per gallon and were compared with similar knock-limited data for S-4 and S-4 plus 2 ml TEL per gallon.

At the higher inlet-air temperature, the knock-limited power of S-4 was slightly decreased at fuel-air ratios below 0.07 by the addition of triethylthallium but was substantially increased at higher fuel-air ratios. When the inlet-air temperature was reduced to 100° F, the knock-limited power of S-4 was appreciably increased at all fuel-air ratios by the addition of triethylthallium. The test fuel containing the triethylthallium was more sensitive, particularly at lean fuel-air ratios, to changes of inlet-air temperature than either S-4 or S-4 plus 2 ml TEL per gallon. At neither inlet-air temperature did the addition of triethylthallium to S-4 produce power increases comparable with those obtained through the addition of an equal-volume concentration of tetraethyl lead.

* * *

Lead Susceptibility of Several Fuels as Determined in an Air-Cooled Aircraft-Engine Cylinder. By Edward G. Stricker, Jerrold D. Wear, and Reece V. Hensley. NACA WR E-220, 1946. (Supersedes NACA RB E6A07.) 4 pp.; 1 table; 7 figs.; Unc.

In order to determine the lead susceptibility of several fuels, leaded and unleaded fuels from the same stock were blended and tested in a full-scale air-cooled aircraft-engine cylinder.

The fuels used were S-4 reference fuel, virgin-base stock, aviation alkylate, neohexane, and blends of 25-percent benzene with 75-percent virgin-base stock and 25-percent toluene with 75-percent virgin-base stock.

Knock-limited performance data were obtained for each fuel, clear and with 6 ml TEL per gallon, for a range of fuel-air ratios from 0.05 or 0.08 to 0.115. Similar data were also obtained for S-4 reference fuel with 2.5 ml TEL per gallon in order to test more thoroughly lead response of a fuel between 0 and 2.5 ml TEL per gallon.

With S-4 reference fuel, a region of slight appreciation in performance was observed between 1 and 1.5 ml TEL per gallon. At higher lead concentrations, a greater response was observed although the incremental increase was smaller for the higher tetraethyl-lead concentrations.

The other fuels were not thoroughly investigated in the range where this break occurred; consequently these fuels may or may not exhibit this peculiarity.

Tests of fuels containing from 0 to 6 ml TEL per gallon at fuel-air ratios from approximately 0.05 to 0.115 made in a full-scale air-cooled aircraft-engine cylinder show that:

1. For tetraethyl-lead concentrations in excess of 3 milliliters per gallon, the aromatic blends showed a greater percentage increase in knock-limited power than the paraffins with the exception of neohexane, which gave the greatest percentage increase of all the fuels tested at lean mixtures. 2956

2. For any particular tetraethyl-lead addition, the percentage increase in knock-limited indicated mean effective pressure compared to the clear fuel was about the same for the aromatic blends tested. The percentage increase in knock-limited mean effective pressure resulting from lead additions varied for the four paraffinic fuels tested.

3. A given lead concentration in any fuel tested permitted a greater percentage increase in knock-limited indicated mean effective pressure at lean mixtures than at rich mixtures.

* * *

The Effects of an Increase in the Concentration of Ethylene Dibromide in a Leaded Fuel on Lead Deposition, Corrosion of Exhaust Valves, and Knock-Limited Power. By B. A. Mulcahy and M. A. Zipkin. NACA WR E-43, 1945. (Supersedes NACA ARR E5E04a.) 5 pp.; 4 figs.; Unc.

In order to determine whether an excess of ethylene dibromide might decrease the amount of unscavenged lead in the cylinder and thereby reduce valve-crown corrosion, two engine tests (tests A and B) were conducted during June and July 1944 at the NACA Cleveland laboratory using a 1-T mix and a 2-T mix (a fuel containing twice the amount of ethylene dibromide theoretically required to combine with the lead) and the amounts of resulting valve corrosion were compared. A third test (test C) was run to investigate the possibility that addition of ethylene dibromide in the fuel might, by combining with the lead, reduce the knock-limited power obtainable with the fuel. Knock-limited indicated mean effective pressure in a Wright C9GC cylinder was determined over a range of fuel-air ratios for 1-T and 2-T mixes of AN-F-28 (28-R) fuel.

The following results were obtained from tests run to determine whether an excess of ethylene dibromide might decrease the amount of unscavenged lead in the cylinder and thereby reduce valve-crown corrosion:

1. When ethylene dibromide in excess of the amount theoretically required to combine with the lead in the fuel (1-T mix) was added, the corrosion of the exhaust-valve crown and the material deposits on the piston and spark plugs were reduced.

2. Fuel containing twice the theoretical amount of ethylene dibromide (2-T mix) produced the same knock-limited indicated mean effective pressure as did fuel containing the theoretical amount of ethylene dibromide (1-T mix).

* * *

<u>Lead Fouling of Aircraft-Engine Spark Plugs. I - Process of Deposit Accumulation.</u> By J. L. Sloop, George R. Kinney, and William H. Rowe. NACA WR E-181, 1945. (Supersedes NACA MR E5K29.) 6 pp.; 6 figs.; Unc.

Tests with CFR and aircraft-type single-cylinder engines were made to investigate the progressive accumulation of lead deposits on spark plugs under nonvarying operating conditions. Deposit-weight determinations and photographic observations are presented, which demonstrate the following characteristics of deposit accumulation:

1. Deposits accumulate at rates that decrease as the total weight of deposit increases.

2. The change in the rate of deposit accumulation with time may differ with different engine operating conditions.

3. Deposits may change their positions on the spark plug during engine operation under the influences of gravitation and molecular forces and, possibly, forces arising from gas flow within the combustion chamber.

* * *

<u>The Effect of Ethylene Dibromide on the Knock-Limited Performance of Leaded and Nonleaded S Reference Fuel.</u> By George R. Kinney and Richard O. Niemi. NACA WR E-183, 1946. (Supersedes NACA MR E6B12.) 6 pp; 1 table; 3 figs.; Unc.

Published tests with an air-cooled, single-cylinder engine showed no reduction in the knock-limited power of an AN-F-28, Amendment-2, fuel when the ethylene-dibromide concentration was increased from 1 theory to 2 theories; however, during tests performed at the NACA Cleveland laboratory on lead fouling of spark plugs, the knock-limited power of a CFR engine decreased when ethylene dibromide was added to nonleaded S reference fuel.

These observations suggested the possibility that the effect of ethylene dibromide on the knock-limited power of an engine might depend upon the concentration of tetraethyl lead in the fuel. Tests therefore conducted on ethylene dibromide on the knock-limited performance of S reference fuel, both leaded and nonleaded to 6 ml TEL per gallon, gave the following results:

1. An increase in the ethylene-dibromide content from 0 to 5.34 milliliters per gallon (0-T to 2-T for 6 ml TEL/gal) decreased the knock-limited power of S reference fuel, both nonleaded and leaded to 6 ml TEL per gallon, approximately the same amount (6 to 9 percent depending upon the fuel-air ratio) except at very lean and very rich fuel-air mixtures where little change in the knock-limited power of the nonleaded fuel was detected. 2956

2. An increase in the ethylene-dibromide content from 0 to 2.67 milliliters per gallon (0-T to 1-T for 6 ml TEL/gal) decreased the knock-limited power of the nonleaded S reference fuel as much as 6 percent depending upon the fuel-air ratios (except at very lean and very rich fuel-air mixtures where little change in the knock-limited power was detected) but had no appreciable effect on the knock-limited power of S reference fuel leaded to 6 ml TEL per gallon.

3. An increase from 0 to 4.01 milliliters per gallon of ethylene dibromide (0-T to 1.5-T for 6 ml TEL/gal) had no appreciable effect on the knock-limited power of S reference fuel leaded to 6 ml TEL per gallon.

* * *

Cross References

<u>The Low-Temperature Solubility of 42 Aromatic Amines in Aviation Gasoline.</u> By Richard L. Kelly. NACA WR E-167, 1945. (Supersedes NACA MR E5K09.) (See VI-C.)

<u>Nitrous Oxide Supercharging of an Aircraft-Engine Cylinder.</u> By Max J. Tauschek, Lester C. Corrington, and Merle C. Huppert. NACA WR E-199, 1945. (Supersedes NACA MR E5F26.) (See I-G.)

<u>Knock-Limited Power Outputs from a CFR Engine Using Internal Coolants. II - Six Aliphatic Amines.</u> By Donald R. Bellman, W. E. Moeckel, and John C. Evvard. NACA WR E-219, 1945. (Supersedes NACA ACR E5H31.) (See I-G.)

<u>Suitability of 18 Aromatic Amines for Overwater Storage When Blended with Aviation Gasoline.</u> By Irving A. Goodman and J. Nelson Howard. NACA WR E-166, 1945. (Supersedes NACA MR E5F20a.) (See VI-C.)

Knock-Limited Performance of Triptane and Xylidines Blended with 28-R Aviation Fuel at High Compression Ratios and Maximum-Economy Spark Setting. By Louis F. Held and Ernest I. Pritchard. NACA RM E6J07, 1946. (See I-C.)

B. Antiknock Blending Agents

Flight and Test-Stand Investigation of High-Performance Fuels in Modified Double-Row Radial Air-Cooled Engines. III - Knock-Limited Performance of 33-R as Compared with a Triptane Blend and 28R in Flight. By Calvin C. Blackman and H. Jack White. NACA WR E-263, 1945. (Supersedes NACA MR E5H08.) 7 pp.; 7 figs.; Unc.

A comparison has been made in flight of the antiknock characteristics of 33-R fuel with that of 28-R and a triptane blend. The knock-limited performance of the three fuels - 33-R, a blend of 80 percent 28-R plus 20 percent triptane (leaded to 4.5 ml TEL/gal), and 28-R - was investigated in two modified 14-cylinder double-row radial air-cooled engines. Tests were conducted on the engines as installed in the left inboard nacelle of an airplane. A carburetor-air temperature of approximately 85° F was maintained. The conditions covered at an engine speed of 2250 rpm were high and low blower ratios and spark advances of 25° and 32° B.T.C. For an engine speed of 1800 rpm only the high-blower condition was investigated for both 25° and 32° spark advances.

For the conditions investigated the difference between 33-R and the triptane blend was found to be slight; the performance of 33-R fuel, however, was slightly higher than that of the triptane blend in the lean region. The knock-limited power obtained with the 33-R fuel was from 14 to 28 percent higher than that of the 28-R fuel for the entire range of test conditions; the greatest improvement was shown in the lean region.

The knock-limited power for any one fuel at a given set of conditions was essentially the same for the two modified engines used in these tests.

* * *

Flight and Test-Stand Investigation of High-Performance Fuels in Modified Double-Row Radial Air-Cooled Engines. II - Flight Knock Data and Comparison of Fuel Knock Limits with Engine Cooling Limits in Flight. By H. Jack White, Philip C. Pragliola, and Calvin C. Blackman. NACA WR E-262, 1945. (Supersedes NACA MR E5H04.) 21 pp.; 1 table; 17 figs.; Unc.

A comparison has been made in flight of the antiknock characteristics of triptane and a temperature-sensitive fuel component (xylidines) with a reference fuel (28-R) and of flight fuel knock limits with engine cooling limits. The knock limits of the three fuels - 28-R, 80 percent 28-R plus 20 percent triptane (leaded to 4.5 ml TEL/gal), and 97 percent 28-R plus 3 percent xylidines (leaded to 6.0 ml TEL/gal) - were investigated in a modified 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane. Tests were conducted at engine speeds of 1800 and 2250 rpm, at high and low blower ratios, spark settings of 25° and 32° B.T.C., and ~~the~~ carburetor-air temperature was maintained at approximately 85° F. All tests for a given engine speed were made with approximately constant cooling-air pressure drop; consequently, engine-temperature levels were higher with the higher performance blends. 2956

A brief survey of the knock-limited performance characteristics of the two fuel blends relative to 28-R follows:

RATIOS OF KNOCK-LIMITED BRAKE HORSEPOWER

OF TEST FUELS RELATIVE TO 28-R

Engine speed, rpm		1800				2250			
Carburetor-air temperature, °F		85				85			
Blower ratio	F/A	Low		High		Low		High	
Fuel blend (volume)		Spark advance, deg B.T.C.							
		25	32	25	32	25	32	25	32
80% 28-R plus 20% triptane leaded to 4.5 ml TEL/gal	0.065	1.15		1.11	1.20	1.21	1.15	1.25	1.13
	.080	1.20		1.20	1.18	1.19	1.17	1.19	1.27
	.090	1.24		1.20	1.19	1.24		1.21	1.27
97% 28-R plus 3% xylidines leaded to 6.0 ml TEL/gal	0.065			1.21	1.17	1.23	1.10	1.21	1.13
	.080			1.27	1.21	1.24	1.20	1.20	1.17
	.090			1.27	1.21	1.26		1.25	

Estimates were made of temperature-limited engine performance at several typical flight and engine conditions. Based on these relations it appears that, if the cooling requirements of the engine are to be governed by the manufacturer's specified maximum rear-spark-plug-gasket temperatures, engine operation at or near fuel knock limits in the economical range of fuel-air ratio may cause these temperatures to be exceeded, particularly at the higher engine speed of 2250 rpm. If it were considered possible to operate with average rear-spark-plug-boss temperatures approaching those experienced with the original model engine (corresponding to maximum rear-spark-plug-gasket temperatures specified for those engines), the cooling limits of the modified engine would be raised and would apparently permit engine operation at or near fuel knock limits under many conditions.

* * *

Flight Investigation of the Knock-Limited Performance of a Triptane Blend, A Toluene Blend, and 28-R Fuel in an R-1830-75 Engine. By Calvin C. Blackman. NACA RM E6I03, 1946. 6 pp.; 1 fig.; Unc.

Knock-limited performance data were obtained for three fuels on an R-1830-75 engine in a B-24D airplane at engine speeds of 1800, 2250, and 2600 rpm, a spark advance of 25° B.T.C., and carburetor-air temperatures of 85° F for 1800 and 2250 rpm and 100° F for 2600 rpm. The test fuels were a blend of 80 percent 28-R plus 20 percent triptane (leaded to 4.5 ml TEL/gal), a blend of 85 percent 28-R plus 15 percent toluene (leaded to 4.5 ml TEL/gal), and 28-R fuel.

The knock-limited manifold pressure of the toluene blend depreciated more in the lean region than the triptane blend or 28-R fuel. The knock-limited brake horsepower for the triptane blend varied from 16 to 25 percent higher than 28-R in the lean region and 18 to 30 percent higher in the rich region. The knock-limited brake horsepower of the toluene blend was approximately 15 percent higher than that of 28-R in the rich region and varied from 2 to 10 percent higher in the lean region.

Knock limits of the triptane blend and 28-R fuel tested in the R-1830-75 engine agreed with limits for the same fuels determined with the R-1830-94 engine for engine speeds of 1800 and 2250 rpm.

* * *

Knock-Limited Performance Tests of 2,2,3,4-Tetramethylpentane, 2,3,3,4-Tetramethylpentane, 3,4,4-Trimethyl-2-Pentane, and 2,3,4-Trimethyl-2-Pentane in Small-Scale and Full-Scale Cylinders. By Edmund R. Jonash, Carl L. Meyer, and J. Robert Branstetter. NACA WR E-236, 1946. (Supersedes NACA ARR E6C04.) 12 pp.; 6 tables; 35 figs.; Unc.

Knock-limited tests were conducted with F-4, F-3, and 17.6 small-scale engines and with a full-scale cylinder on blends containing the following purified hydrocarbons:

2,2,3,4-Tetramethylpentane
2,3,3,4-Tetramethylpentane
3,4,4-Trimethyl-2-pentene
2,3,4-Trimethyl-2-pentene

Each of the four hydrocarbons was individually blended in various concentrations with three base fuels: S-4 reference fuel, S-4 plus 4 ml TEL per gallon in the final blend, and a blend of 87.5 percent S-4 plus

12.5 percent *n*-heptane plus 4 ml TEL per gallon in the final blend. Data were obtained for the four hydrocarbons to determine the following antiknock characteristics: (a) blending sensitivity, (b) sensitivity of the blends to inlet-air temperature, (c) lead susceptibility of the blends, and (d) correlation of full-scale and small-scale engine results.

From these knock-limited tests of two paraffinic and two olefinic hydrocarbons, the following results were obtained:

In general, the two paraffins - 2,2,3,4-tetramethylpentane and 2956
2,3,3,4-tetramethylpentane - were effective in increasing the knock-limited performance of the base fuels particularly at rich mixtures. In most instances the 2,3,3,4-tetramethylpentane blend gave the higher knock-limited performance at rich mixtures.

With some exception, the olefin 3,4,4-trimethyl-2-pentene increased the knock-limited performance of the base fuels only at mild conditions, and 2,3,4-trimethyl-2-pentene acted as a proknock agent under most of the conditions tested.

The knock-limited performance of the hydrocarbon blends was ordinarily more sensitive to changes of inlet-air temperature than the knock-limited performance of the base fuel. At rich mixtures, the temperature sensitivity of the olefinic blends was considerably greater than that of the paraffinic blends.

In most cases, the hydrocarbon blends showed greater lead susceptibility than the base fuel. At the higher inlet-air temperature tested and at lean mixtures, the paraffins were more susceptible to lead additions than the olefins.

The correlations of the full-scale and small-scale engine results indicate that the test results agree more closely with the full-scale cylinder operating at the modified cruise conditions. In general, the F-3 and F-4 engines rated the hydrocarbons considerably lower than the full-scale cylinder, and the 17.6 engine somewhat higher than the full-scale cylinder.

* * *

The Knock-Limited Performance of Fuel Blends Containing Spiropentane, Methylenecyclobutane, Di-tert-Butyl Ether, Methyl tert-Butyl Ether, and Triptane. By Carl L. Meyer. NACA WR E-222, 1946. (Supersedes NACA RB E6D22.) 2 pp.; 1 table; 2 figs.; Unc.

A general investigation was conducted at the NACA Cleveland laboratory to determine the effectiveness of various compounds as antiknock agents for aviation fuels. As a part of this program, limited quantities of spiropentane, methylenecyclobutane, and di-*tert*-butyl ether were synthesized for exploratory tests. Methyl *tert*-butyl ether and triptane, which had been commercially obtained, were used for comparative purposes. Knock-limited tests were made in a 17.6 engine of blends containing each of the five compounds individually blended with S-4 reference fuel to a concentration of 20 percent by volume; the final blends contained 4 ml TEL per gallon.

The 20-percent addition of spiropentane decreased the knock-limited power of the base fuel at all fuel-air ratios below 0.085 but permitted gains at richer fuel-air mixtures. Methylenecyclobutane decreased the knock-limited power of the base fuel at all fuel-air ratios below 0.112. Because of the lack of material, knock-limited performance data were not obtained for the spiropentane blend at fuel-air ratios greater than 0.10; additional tests to determine the effect of a change in inlet-air temperature on the knock-limited performance of either of the two aforementioned blends were not possible for the same reason.

Di-*tert*-butyl ether, methyl *tert*-butyl ether, and triptane increased the knock-limited power of the base fuel at all fuel-air ratios and at both inlet-air temperatures. Methyl *tert*-butyl ether was the most effective antiknock agent of the three compounds. Di-*tert*-butyl ether was more effective than triptane at fuel-air ratios below 0.07 at the higher inlet-air temperature and at all fuel-air ratios at the lower inlet-air temperature. (Under other test conditions, NACA WR E-165, 1945, showed that di-*tert*-butyl ether had better antiknock qualities than methyl *tert*-butyl ether at fuel-air ratios below about 0.065.) Blends containing the three compounds are more sensitive at fuel-air ratios of 0.065 and 0.07 to changes in inlet-air temperature than the base fuel; methyl *tert*-butyl ether was the most sensitive in the aforementioned fuel-air-ratio range.

* * *

Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in A Full-Scale Aircraft-Engine Cylinder. III - Four Aromatics, Six Ethers. By Anthony W. Jones, Arthur W. Bull, and Edmund R. Jonash. NACA WR E-235, 1946. (Supersedes NACA ARR E6B14.) 8 pp.; 1 table; 8 figs.; Unc.

Knock-limited performance tests of leaded blends of four pure aromatic hydrocarbons and six pure ethers with a base fuel were conducted in a full-scale aircraft-engine cylinder at two operating conditions to determine the antiknock effectiveness of additions of pure compounds to aviation fuels. The following fuels were tested:

n-Butylbenzene
Isobutylbenzene
n-Propylbenzene
1-Isopropyl-4-methylbenzene (p-cymene)

Methyl *tert*-butyl ether
Ethyl *tert*-butyl ether
Isopropyl *tert*-butyl ether
Methyl phenyl ether (anisole)
Ethyl phenyl ether (phenetole)
Methyl *p*-tolyl ether

Each of these fuels was blended with a base fuel ($87\frac{1}{2}$ percent S-4 and $12\frac{1}{2}$ percent *n*-heptane plus 4 ml TEL/gal) and the final blend was leaded to 4.0 ml TEL per gallon. The four aromatics were blended to a concentration of 25 percent by volume and the ethers were blended to a concentration of 10 percent by volume in the base fuel. The base fuel and a fuel consisting of 85 percent S-4 and 15 percent M-4 plus 4.0 ml TEL per gallon were also tested separetely. Curves of S-4 reference fuels having lead concentrations up to 4.0 ml TEL per gallon were obtained to bracket most of the test-fuel curves. 2956

The data obtained from knock tests on a full-scale aircraft-engine cylinder indicate that:

1. The four aromatic hydrocarbons increased the knock limit of the base fuel at both operating conditions and *p*-cymene gave the greatest increase at all conditions with the exception of isobutylbenzene, which developed equivalent power in the lean region (0.06 to 0.075 fuel-air ratio) under the modified CRC cruise conditions.

2. The six ethers increased the knock-limited power of the base fuel at both operating conditions. Methyl *tert*-butyl ether gave the greatest increase throughout the normal fuel-air-ratio range at the CRC cruise conditions. Methyl *tert*-butyl ether also gave the greatest improvement at the modified cruise conditions except at fuel-air ratios leaner than 0.065 where ethyl *tert*-butyl ether gave an equivalent increase in knock-limited performance.

* * *

Knock-Limited Performance of *n*-Methylaniline and Xylidine Blends in an Air-Cooled Aircraft Cylinder. By Arthur W. Bull, Edward G. Stricker, and Jerrold D. Wear. NACA WR E-109, 1946. (Supersedes NACA ARR E6A28.) 4 pp.; 1 table; 5 figs.; Unc.

In order to compare the antiknock effectiveness of *n*-methylaniline and xylidines as fuel additives under severe engine operating conditions, 5-percent concentrations by weight were blended with an alkylate blending agent and a virgin-base gasoline. The *n*-methylaniline was also blended in a 5-percent concentration with a base fuel containing 75 percent (by weight) virgin-base gasoline and 25 percent toluene. All blends contained 4 ml TEL per gallon. The knock-limited performance of each of these aromatic-amine blends was compared with the knock-limited performance of the leaded base fuels in an air-cooled aircraft-engine cylinder. As a fuel antiknock additive, n-methylaniline was equal to or better than xylidines. Neither n-methylaniline nor xylidines is of value as a fuel antiknock additive in the lean-mixture region.

* * *

Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. II - Investigation of Leaded Paraffinic Fuels in an Air-Cooled Cylinder. By Jerrold D. Wear and Newell D. Sanders. NACA TN 1374, 1947. (Supersedes NACA MR's E5C14 and E4J01.) 8 pp.; 2 tables; 18 figs.; Unc.

The relation between knock limit and blend composition of selected avaition fuel components individually blended with virgin base and with alkylate was determined in a full-scale air-cooled aircraft-engine cylinder. In addition the following correlations were examined:

(a) The knock-limited performance of a full-scale engine at lean-mixture operation plotted against the knock-limited performane of the engine at rich-mixture operation for a series of fuels.

(b) The knock-limited performance of a full-scale engine at rich-mixture operation plotted against the knock-limited performance at rich-mixture operation of a small-scale engine for a series of fuels.

In each case the following methods of specifying the knock-limited performance of the engine were investigated:

(1) Knock-limited indicated mean effective pressure.

(2) Percentage of S-4 plus 4 ml TEL per gallon in M-4 plus 4 ml TEL per gallon to give an equal knock-limited indicated mean effective pressure.

(3) Ratio of indicated mean effective pressure of test fuel to indicated mean effective pressure of clear S-4 reference fuel, all other conditions being the same.

Results indicated that the knock-limited indicated mean effective pressures of the paraffinic fuels investigated, except the neohexane blends at lean mixtures for a spark advance of 20° B.T.C., followed the reciprocal blending equation provided that the temperature of the cylinder walls near the knocking zone was held constant.

Percentage of S-4 reference fuel in M-4 reference fuel (both fuels containing 4 ml TEL/gal) for an equal knock-limited indicated mean effective pressure of the paraffinic fuels tested at a spark advance of

20° B.T.C. gave ratings of the paraffinic fuels that were independent of the type of engine used in these tests and of the fuel-air ratio.

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Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. III - Aromatics and Cycloparaffins. By I. L. Drell and J. D. Wear. NACA TN 1416, 1947. 11 pp.; 1 table; 8 figs.; Unc.

The knock-limited power at various blend compositions for several aromatics and cycloparaffins individually blended with paraffinic base stocks, was determined in an air-cooled aircraft-engine cylinder at fuel-air ratios of 0.07 and 0.10. An analysis of the data leads to the conclusion that the extended reciprocal blending relation suggested in a previous NACA report is not generally applicable to such nonparaffinic components, but might possibly be useful as an approximation over a limited range of composition for aromatic blends. 2956

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The Knock-Limited Performance of Fuel Blends Containing Aromatics. V - n-Propylbenzene, n-Butylbenzene, Isobutylbenzene, m-Xylene, and 1-Isopropyl-4-Methylbenzene. By Carl L. Meyer and J. Robert Branstetter. NACA WR E-237, 1946. (Supersedes NACA ARR E6C05.) 10 pp.; 5 tables; 29 figs.; Unc.

Knock-limited tests were made of n-propylbenzene, n-butylbenzene, isobutylbenzene, m-xylene, and 1-isopropyl-4-methylbenzene blended individually in various concentrations with selected base fuels. Data were obtained for the five aromatics to determine: (a) the blending sensitivity, (b) the sensitivity of the blends to inlet-air temperatures, (c) the lead susceptibility of the blends, and (d) the correlation of small-scale and full-scale engine results. The data presented herein were obtained with small-scale engines; published full-scale single-cylinder engine data are presented for comparison.

The five aromatics in most instances rated in the following order of decreasing antiknock effectiveness in leaded blends at a fuel-air ratio of 0.10: m-xylene, 1-isopropyl-4-methylbenzene, n-propylbenzene, isobutylbenzene, and n-butylbenzene. At lean mixtures these aromatics, with the exception of n-butylbenzene, which had the lowest response at most conditions, were comparable as antiknock blending agents.

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Knock-Limited Performance of Fuel Blends Containing Aromatics. VI - 10 Alkylbenzenes. By I. L. Drell and H. E. Alquist. NACA TN 1994, 1949. 10 pp.; 4 tables; 6 figs.; Unc.

Knock-limited engine data are given for 10 aromatics, each in blends with base fuels. The aromatics are 1,2,3-trimethylbenzene, 1-ethyl-2-methylbenzene, o-diethylbenzene, 1,3-dimethyl-5-ethylbenzene, 1-ethyl-3-methylbenzene, p-diethylbenzene, 1,3,5-triethylbenzene, 1,3-diethyl-5-methylbenzene, 1-tert-butyl-3-methylbenzene, and 1-tert-butyl-4-methylbenzene. The engines used were the A.S.T.M. Aviation, A.S.T.M. Supercharge, a 17.6 engine (run at two inlet-air temperatures), and a modified CFR engine (run at five compression ratios).

The aromatic blends rated in about the order given (1,2,3-trimethylbenzene being poorest), considering the whole range of conditions studied. The three aromatics with ortho structures generally gave much lower blend knock ratings than the other seven aromatics. The differences within each group were not large.

A 25-percent blend of the better aromatics with a 120/110 base fuel raised both lean and rich performance numbers: A.S.T.M. Aviation values went up 50 percent or less; rich A.S.T.M. Supercharge values went up about 50 percent.

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<u>Antiknock Evaluation of Hydrocarbons and Ethers as Aviation Fuel Components.</u> By Henry C. Barnett. NACA RM E50H02, 1950. 54 pp.; 11 tables; 13 figs.; Unc.

The results of a NACA investigation conducted over a period of several years to evaluate the antiknock characteristics of organic compounds are summarized. Included are data for 18 branched paraffins and olefins, 27 aromatics, and 22 ethers.

The factors of performance investigated were blending characteristics, temperature sensitivity, lead response, and relation between molecular structure and antiknock ratings. Four engines were used in these studies.

On the basis of an investigation of the type reported herein, it is difficult to draw any specific conclusions, inasmuch as antiknock characteristics are influenced by many factors. The relative order of antiknock ratings of a series of compounds is influenced by engine conditions, by the tetraethyl lead content, and by the concentration of blending agent in the base fuel with which a comparison is made. With consideration for these factors, tert-butylbenzene, methyl and ethyl tert-butyl ethers, and 2,2,3-trimethylbutane and several nonanes were among the best compounds in their respective organic classes. This selection was based upon temperature sensitivity and lead susceptibility as well as antiknock value.

In an effort to generalize the data obtained in this investigation, the subsequent conclusions are expressed in terms of the relation of various performance factors to the gasoline boiling range as influenced by the classes of organic compounds investigated. Furthermore, these conclusions must necessarily be restricted to the limitations of this investigation and therefore cannot be applied without exception.

Antiknock ratings. - In the low-boiling gasoline range, the highest antiknock ratings are among the more volatile paraffins and ethers. In the intermediate gasoline range, the ethers excel; in the high-boiling range the aromatics have the highest antiknock ratings.

Temperature sensitivity. - In the low-boiling gasoline range, the data are incomplete as regards temperature sensitivity, but there are indications that the volatile ethers are more sensitive to temperature changes than are the paraffins or aromatics. In the intermediate and high-boiling ranges of gasoline, the aromatics are more sensitive to temperature than the paraffins and the ethers. Moreover, the aromatics that have the highest antiknock ratings are also sensitive to temperature.

Lead susceptibility. - In the low-boiling gasoline range, the data are incomplete as regards lead susceptibility, but there are indications that the more volatile ethers are more susceptible to additions of tetraethyl lead than are the paraffins and the aromatics. In the intermediate and high-boiling ranges of gasoline, the aromatics show greater lead susceptibility than either the paraffins or the ethers.

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Knock-Limited Performance of Fuel Blends Containing Ethers. By I. L. Drell and J. R. Branstetter. NACA TN 2070, 1950. 18 pp.; 10 tables; 10 figs.; Unc.

Knock ratings are given for 23 ethers, each blended with base fuels. A.S.T.M. Aviation, A.S.T.M. Supercharge, aircraft single-cylinder, and 17.6 engine ratings are presented. Fuel consumption, blending characteristics, temperature sensitivity, and lead susceptibility are also briefly discussed.

Methyl tert-butyl ether appeared to have the best over-all antiknock effectiveness, considering all blend compositions and engine conditions investigated. In general, tert-butyl alkyl ethers gave the highest blend knock ratings, followed by aromatic alkyl ethers; ethers with olefinic, cycloparaffinic, and ortho aromatic groups gave the lowest ratings.

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Cross References

A Method of Estimating the Knock Rating of Hydrocarbon Fuel Blends. By Newell D. Sanders. NACA Rep. No. 760, 1943. (Supersedes NACA ARR 3H21.) (See I-D.)

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Correlation of the Characteristics of Single-Cylinder and Flight Engines in Tests of High-Performance Fuels in an Air-Cooled Engine. II - Knock-Limited Charge-Air Flow and Cylinder Temperatures. By Kenneth D. Brown, Paul H. Richard, and Robert W. Wilson. NACA WR E-272, 1945. (Supersedes NACA MR E5J12.) (See I-D.)

Knock-Limited Performance of Triptane and Xylidines Blended with 28-R Aviation Fuel at High Compression Ratios and Maximum-Economy Spark Setting. By Louis F. Held and Ernest I. Pritchard. NACA RM E6J07, 1946. (See I-C.)

Investigation of High-Performance Fuels in Multicylinder and in Single-Cylinder Engines at High and Cruising Engine Speeds. By Arthur H. Bell, R. Lee Nelson, and Paul H. Richard. NACA RM E7A30, 1947. (See I-C.)

Knock-Limited Performance of Triptane and 28-R Fuel Blends as Affected by Changes in Compression Ratio and in Engine Operating Variables. By Rinaldo J. Brun, Melvin S. Feder, and William F. Fisher. NACA RM E7A21a, 1947. (See I-C.)

Knock-Limited Power Outputs from a CFR Engine Using Internal Coolants. III - Four Alkyl Amines, Three Alkanolamines, Six Amides, and Eight Heterocyclic Compounds. By Harry S. Imming and Donald R. Bellman. NACA RM E6L05a, 1947. (See I-G.)

Estimation of F-3 and F-4 Knock-Limited Performance Ratings for Ternary and Quaternary Blends Containing Triptane or Other High-Antiknock Aviation-Fuel Blending Agents. By Henry C. Barnett. NACA Rep. 904, 1948. (Supersedes NACA WR E-250.) (See I-D.)

Knock-Limited Performance of Several Branched Paraffins and Olefins. By R. S. Genco and I. L. Drell. NACA TN 1616, 1948. (See I-C.)

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C. Effect of Operating Variables on Knock-Limited Performance

Comparison of Relative Sensitivities of the Knock Limits of Two Fuels to Six Engine Variables. By Harvey A. Cook, Louis F. Held, and Ernest I. Pritchard. NACA TN 1117, 1946. 7 pp.; 13 figs.; Unc.

A sensitive fuel (42 percent S reference fuel, 40 percent toluene, and 18 percent M reference fuel by volume + 4 ml TEL/gal; grade 103/145) and a relatively insensitive fuel (100 percent S reference fuel + 4 ml TEL/gal; grade 153/153) were knock-tested in a full-scale air-cooled cylinder. Sensitivity was indicated by different degrees of knock-limited response to changes in engine conditions. Six engine variables were investigated: (1) fuel-air ratio, (2) compression ratio, (3) inlet-air temperature, (4) spark advance, (5) exhaust pressure, and (6) cylinder temperature.

The relative changes in the knock-limited indicated mean effective pressure and charge-air flow of the two fuels were different for the six engine variables, and, except for cylinder temperature, varied over the range investigated. These results indicate that, in order to correlate the effects of engine variables on knock-limited performance of fuels, more basic knock factors than knock-limited indicated mean effective pressure and charge-air flow are required. Fuel-air ratios above the stoichiometric showed the greatest relative sensitivity of the knock limits of the two fuels except for tests at high exhaust pressure. The 2356
relative sensitivities shown in fuel-air-ratio and exhaust-pressure tests became more consistent with those for the other engine variables when the fuel-air-ratio data were compared on a percentage excess fuel basis rather than on a fuel-air basis and the exhaust-pressure data were compared on either an exhaust to inlet pressure ratio basis or inlet to exhaust-pressure difference basis rather than on the basis of exhaust pressure.

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Correlation of the Characteristics of Single-Cylinder and Flight Engines in Tests of High-Performance Fuels in an Air-Cooled Engine. II - Knock-Limited Charge-Air Flow and Cylinder Temperatures. By Kenneth D. Brown, Paul H. Richard, and Robert W. Wilson. NACA WR E-272, 1945. (Supersedes NACA MR E5J12.) 5 pp.; 3 figs.; Unc.

An investigation was conducted to correlate the knock-limited performance of flight and single-cylinder engines under a variety of operating conditions. Knock-limited performance of 28-R, triptane blend, and xylidine blend was determined on a full-scale air-cooled single cylinder mounted on a CUE crankcase. The inlet-air temperatures were such that the mixture temperatures were the same as the multicylinder engine with high and low blower ratios.

The single-cylinder engine knock-limited charge-air flow is in good agreement with that of the flight engine for all engine operating conditions tested. Similarly head temperatures for the two engines showed good agreement, but the barrel temperatures for the flight engine were higher than for the single-cylinder engine. The performance of the fuels on the basis of knock-limited charge-air flow were in the order xylidine blend > triptane blend > 28-R fuel.

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Knock-Limited Performance of Triptane and Xylidines Blended with 28-R Aviation Fuel at High Compression Ratios and Maximum-Economy Spark Setting. By Louis F. Held and Ernest I. Pritchard. NACA RM E6J07, 1946. 15 pp.; 2 tables; 10 figs.; Unc.

An investigation was conducted to evaluate the possibilities of utilizing the high-performance characteristics of triptane and xylidines blended with 28-R fuel in order to increase fuel economy by the use of high compression ratios and maximum-economy spark setting.

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Full-scale single-cylinder knock tests were run with 20° B.T.C. and maximum-economy spark settings at compression ratios of 6.9, 8.0, and 10.0, and with two inlet-air temperatures. The fuels tested consisted of triptane, four triptane and one xylidines blend with 28-R, and 28-R fuel alone.

At a fuel-air ratio of 0.065, 20-percent triptane blended with 28-R fuel gave increases in knock-limited indicated power ranging from 4 to 28 percent relative to 28-R fuel; and 3-percent xylidines blended with 28-R gave increases ranging from -4 to 37 percent. The maximum observed increase was 78 percent. This increase was obtained with 100-percent triptane at a compression ratio of 10.0 and an inlet-air temperature of 150° F. This value would probably have been exceeded if 100-percent triptane had been knock-tested at a lower compression ratio.

In general, the knock-limited performance of the xylidines blend was affected more by changes in severity of engine operating conditions than the 20-percent triptane blend and relative to 28-R fuel, the knock-limited performance of both blends was less favorable as the severity of engine operating conditions was raised by increases in compression ratio, inlet-air temperature, and spark setting.

When compression ratio was increased from 6.9 to 10.0 at an inlet-air temperature of 150° F, normal spark setting, and a fuel-air ratio of 0.065, 55-percent triptane was required with 28-R fuel to maintain the knock-limited brake power level obtained with 28-R fuel at a compression ratio of 6.9.

For concentrations up through at least 20 percent, triptane can be more efficiently used at normal than at maximum-economy spark setting to maintain a constant knock-limited power output over the range of compression ratios tested.

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Investigation of High-Performance Fuels in Multicylinder and in Single-Cylinder Engines at High and Cruising Engine Speeds. By Arthur H. Bell, R. Lee Nelson, and Paul H. Richard. NACA RM E7A30, 1947. 10 pp.; 8 figs.; Unc.

An investigation was conducted to compare the knock-limited performance of a 20-percent triptane blend in 28-R fuel with that of 28-R and 33-R fuels at high engine speeds, cruising speeds, and two compression ratios in an R-1830-94 multicylinder engine.

Data were obtained with the standard compression ratio of 6.7 and with a compression ratio of 8.0. The three fuels were investigated at engine speeds of 1800, 2250, 2600, and 2800 rpm at high and low blower ratios. A carburetor-air temperature of approximately 100° F was maintained for the multicylinder-engine runs. Data were obtained on a single R-1830-94 cylinder engine as a means of checking the multicylinder data at the higher speeds.

A satisfactory correlation between average mixture temperature and knock-limited manifold pressure was obtained by plotting knock-limited manifold pressure against average mixture temperature for the whole range of engine speeds at constant carburetor-air temperature and cylinder-head temperature. The single-cylinder knock-limited performance based on charge-air flow matched that of the multicylinder engine within 6 percent under all the conditions except for 28-R fuel at 2800 rpm; these curves differed from each other by 11 percent in the rich region. The knock rating of 33-R fuel was found to be a little higher than that of the 20-percent triptane blend and 28-R fuel at high mixture temperatures (above 210° F) and lean mixtures. The 33-R fuel exhibited rich knock limits appreciably lower than the 20-percent triptane blend. Increasing the compression ratio from 6.7 to 8.0 lowered the knock-limited manifold pressure for all fuels approximately 15 to 18 inches of mercury absolute in the cruising range and 20 to 28 inches of mercury absolute at higher engine speeds. Brake specific fuel consumption was reduced 7 to 9 percent by the increase in compression ratio from 6.7 to 8.0.

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<u>Knock-Limited Performance of Triptane and 28-R Fuel Blends as Affected by Changes in Compression Ratio and in Engine Operating Variables.</u> By Rinaldo J. Brun, Melvin S. Feder, and William F. Fisher. NACA RM E7A21a, 1947. 9 pp.; 3 tables; 6 figs.; Unc.

A knock-limited performance investigation was conducted on blends of triptane and 28-R fuel with a 12-cylinder, V-type, liquid-cooled aircraft engine of 1710-cubic-inch displacement at three compression ratios: 6.65, 7.93, and 9.68. At each compression ratio, the effect of changes in temperature of the inlet air to the auxiliary-stage supercharger and in fuel-air ratio was investigated at engine speeds of 2280 and 3000 rpm.

The results show that knock-limited engine performance, as improved by the use of triptane, allowed operation at both take-off and cruising power at a compression ratio of 9.68. At an inlet-air temperature of 60° F, an engine speed of 3000 rpm, and a fuel-air ratio of 0.095 (approximately take-off conditions), a knock-limited engine output of 1500 brake horsepower was possible with 100-percent 28-R fuel at a compression ratio of 6.65; 20-percent triptane was required for the same power output at a compression ratio of 7.93, and 75 percent at a compression ratio of 9.68 allowed an output of 1480 brake horsepower.

Knock-limited power output was more sensitive to changes in fuel-air ratio as the engine speed was increased from 2280 to 3000 rpm, as the compression ratio is raised from 6.65 to 9.68, or as the inlet-air temperature is raised from 0° to 120° F.

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<u>Knock-Limited Performance of Several Branched Paraffins and Olefins.</u> By R. S. Genco and I. L. Drell. NACA TN 1616, 1948. 12 pp.; 7 tables; 6 figs.; Unc.

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The knock-limited performance of 2,2,3,3-tetramethylpentane, 2,4-dimethyl-3-ethylpentane, 2,3-dimethylpentane, and 2,3-dimethyl-2-pentene, individually blended in several base fuels was determined in F-3, F-4, and supercharged 17.6 engines. Temperature sensitivity of the fuels is shown by compression temperature-density curves computed from knock data at five compression ratios on a modified F-4 engine; these curves are also presented for blends of 2,3,4-trimethyl-2-pentene and 3,4,4-trimethyl-2-pentene, whose knock-limited performance was previously reported.

The engine conditions of this investigation are roughly classified as to degree of severity and this concept is used in comparing these compounds with other selected hydrocarbons.

Of a group of high-performance paraffins, the 2,2,3,3-tetramethylpentane blend was the best for high knock-limit at conditions of mild or moderate engine severity, but at more severe conditions it was the poorest of the group; at severe conditions (F-3), the triptane blend was the best; at very severe conditions, more severe than F-3, the relatively insensitive fuels such as isooctane were thought to be as good as or better than any of the others. For high antiknock performance in blends over a fairly wide range of engine severity, triptane may still be considered the best liquid paraffinic hydrocarbon known.

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Cross References

<u>Flight and Test-Stand Investigation of High-Performance Fuels in Modified Double-Row Radial Air-Cooled Engines. II - Flight Knock Data and Comparison of Fuel Knock Limits with Engine Cooling Limits in Flight.</u> By H. Jack White, Philip C. Pragliola, and Calvin C. Blackman. NACA WR E-262, 1945. (Supersedes NACA MR E5H04.) (<u>See I-B.</u>)

<u>A Relation Between Knock-Limited or Preignition-Limited Air-Fuel Ratio at Lean Mixtures and Fuel-Air Ratio at Rich Mixtures.</u> By John C. Evvard. NACA WR E-208, 1945. (Supersedes NACA CB E5J11.) (<u>See I-D.</u>)

<u>An Evaluation of the Knock-Limited Performance of Triptane.</u> By Henry C. Barnett. NACA WR E-276, 1946. (Supersedes NACA MR E6B20.) (<u>See I-D.</u>)

A Correlation of the Effects of Compression Ratio and Inlet-Air Temperature on the Knock Limits of Aviation Fuels in a CFR Engine - II. By Henry E. Alquist, Leon O'Dell, and John C. Evvard. NACA WR E-240, 1946. (Supersedes NACA ARR E6E13.) (See I-D.)

An Evaluation of Proposed Reference Fuel Scales for Knock Rating. By Henry C. Barnett and Thomas C. Clarke. NACA TN 1619, 1948. (See I-D.)

Correlation of Effects of Fuel-Air Ratio, Compression Ratio, and Inlet-Air Temperature on Knock Limits of Aviation Fuels. By Leonard K. Tower and Henry E. Alquist. NACA TN 2066, 1950. (See I-D.) 2956

Knock-Limited Performance of Fuel Blends Containing Aromatics. VI - 10 Alkylbenzenes. By I. L. Drell and H. E. Alquist. NACA TN 1994, 1949. (See I-B.)

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D. Correlation Studies

A Method of Estimating the Knock Rating of Hydrocarbon Fuel Blends. By Newell D. Sanders. NACA Rep. 760, 1943. (Supersedes NACA ARR 3H21.) 7 pp.; 8 fig.; Unc.

The usefulness of the knock ratings of pure hydrocarbon compounds would be increased if some reliable method of calculating the knock ratings of fuel blends was known. The purpose of this study was to investigate the possibility of developing a method of predicting the knock ratings of fuel blends.

Two blending equations have been derived from an analysis based on certain assumptions relative to the cause of fuel knock: One of these equations may be used for calculating the knock limit of fuel blends when tested in a supercharged test engine. This equation indicates that the reciprocal of the knock-limited inlet-air density of a fuel equals the weighted average of the reciprocals of the knock-limited inlet-air densities of the pure components. The same law applies when indicated mean effective pressure is used in place of inlet-air density.

The second blending equation may be used for calculating the knock limit of fuel blends when tested by critical-compression-ratio methods. The equation relates the blending characteristics of fuels to the knock limits of the pure fuels and to blending constants that appear in the equation.

The limited amount of experimental data available seems to be in agreement with the theory except in the case of benzene. Although the blending equations do not apply to all fuels and the experimental data are not extensive enough to delineate the limits of applicability, it is believed that the analysis presented will be of assistance in understanding the relations that exist between the knock-testing of pure and of blended fuels.

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<u>A Relation Between Knock-Limited or Preignition-Limited Air-Fuel Ratio at Lean Mixtures and Fuel-Air Ratio at Rich Mixtures.</u> By John C. Evvard. NACA WR E-208, 1945. (Supersedes NACA CB E5J11.) 6 pp.; 2 figs.; Unc.

2956

A derivation is presented to show that, if the <u>air-fuel</u> ratio at lean mixtures is plotted against the fuel-air ratio at rich mixtures for identical values of the knock-limited (or preignition-limited) indicated mean effective pressure on each side of the minimum indicated-mean-effective-pressure point, a straight line should result. This linear relation is checked for several cases of knock-limited and preignition-limited CFR engine data. The correlation obtained indicates that the influential variables controlling the knock-limited (or preignition-limited) performance of a fuel in the lean-mixture and rich-mixture branches of the performance curve are related.

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<u>An Evaluation of the Knock-Limited Performance of Triptane.</u> By Henry C. Barnett. NACA WR E-276, 1946. (Supersedes NACA MR E6B20.) 12 pp.; 8 figs.; Unc.

An analysis is made of data obtained in an experimental investigation of the knock-limited performance of triptane. Data obtained in the F-3 and F-4 rating engines, two full-scale air-cooled aircraft cylinders, and flight tests of a full-scale multicylinder engine are discussed. As a means of evaluating triptane, use is made of the relation between compression densities and temperatures as well as the reciprocal blending equation used in previous NACA reports. The knock-limited performance of triptane is expressed in terms of F-3 and F-4 ratings, alkylate-replacement values, sensitivity to different degrees of engine severity, and lead susceptibility.

Within the limitations of this evaluation of the knock-limited performance of triptane, the following results are apparent:

1. Triptane leaded to 4 ml TEL per gallon has an F-3 performance number of 149 and an extrapolated F-4 performance number of 360.

2. In comparison with paraffinic fuels (diisopropyl, hot-acid octane, neohexane, isopentane, and aviation alkylate) triptane had the highest F-3 rating (with the exception of neohexane) and the highest F-4 rating. Although the F-3 rating of methyl <u>tert</u>-butyl ether (> 166) could not be accurately determined, it was greater than the rating of triptane (149). The data for F-4 tests of four aromatics and methyl

tert-butyl ether could not be accurately extrapolated; it is probable, *however*, that some of the aromatics and methyl *tert*-butyl ether have F-4 ratings equal to or greater than triptane.

3. Small-scale engine data at two inlet-air temperatures showed that the lead susceptibility of triptane at lean and rich fuel-air mixtures is considerably less than that of the aromatic fuels with which it was compared. The lead susceptibility of triptane is slightly greater than that of S reference fuel at the conditions examined. 2956

4. Compression temperature-density data obtained on a small-scale engine and on an R-2800 full-scale single-cylinder test engine indicate that the knock-limited performance of triptane at the more severe conditions is sensitive to changes in operating conditions. In the small-scale engine tests at severe conditions, triptane leaded to 4 ml TEL per gallon had a lower knock-limited performance than S reference fuel, toluene, aviation alkylate, and diisopropyl (all leaded to 4 ml TEL/gal) at a fuel-air ratio of 0.065. In these same tests, however, the knock-limited performance of triptane was appreciably better than all fuels with which it was compared at mild conditions and both low and high fuel-air ratios. The R-2800 tests showed that under severe conditions the improvement in knock-limited performance to be gained by addition of 20 percent triptane to 28-R fuel was small.

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A Correlation of the Effects of Compression Ratio and Inlet-Air Temperature on the Knock Limits of Aviation Fuels in a CFR Engine - II. By Henry E. Alquist, Leon O'Dell, and John C. Evvard. NACA WR E-240, 1946. (Supersedes NACA ARR E6E13.) 9 pp.; 22 figs.; Unc.

The knock-limited performance of nine fuels, comprising isolated members of four classes of hydrocarbons (aromatics, paraffins, cycloparaffins, and olefins), is presented in the form of three-dimensional plots of fuel-air ratio, compression temperature, and compression-air density. The plots are based on a correlation that is shown to apply for these fuels over a wide range of compression ratios and inlet-air temperatures. The significance of the term "temperature sensitivity" is sketched, and it is emphasized that no generalized number such as octane number can be applied even to members of a given class of hydrocarbons when broad ranges of engine severity are encountered.

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An Evaluation of Proposed Reference Fuel Scales for Knock Rating. By Henry C. Barnett and Thomas C. Clark. NACA TN 1619, 1948. 12 pp.; 4 tables; 21 figs.; Unc.

Proposed reference-fuel scales for measuring the knocking tendencies of aviation fuels were investigated to ascertain possible limitations from consideration of sensitivity to changes of engine operating conditions and consideration of the range of knock-limited performance by which the proposed scales would extend current rating scales. The investigation was conducted entirely in F-3 and F-4 aviation fuel-rating engines.

It is concluded that the proposed reference-fuel combinations are comparable in temperature sensitivity with typical aviation fuel blends and will extend the range of knock-limited performance of current rating scales by an appreciable amount when used with satisfactory rating engines. On the other hand, difficulties with the occurrence of pre-ignition in the F-4 engine and the severity of operating conditions in the F-3 engine indicate that these two engines in present form and under present specified operating conditions are inadequate for rating aviation fuel having performance numbers in excess of 161.

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Estimation of F-3 and F-4 Knock-Limited Performance Ratings for Ternary and Quaternary Blends Containing Triptane or Other High-Antiknock Aviation-Fuel Blending Agents. By Henry C. Barnett. NACA Rep. 904, 1948. 21 pp.; 3 tables; 13 figs.; Unc.

Charts are presented that permit the estimation of F-3 and F-4 knock-limited performance ratings for certain ternary and quaternary fuel blends. Ratings for various ternary and quaternary blends estimated from these charts compare favorably with exerpimental F-3 and F-4 ratings. Because of the unusual behavior of some of the aromatic blends in the F-3 engine, the charts for aromatic-paraffinic blends are probably less accurate than the charts for purely paraffinic blends.

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Correlation and Effects of Fuel-Air Ratio, Compression Ratio, and Inlet-Air Temperature on Knock Limits of Aviation Fuels. By Leonard K. Tower and Henry E. Alquist. NACA TN 2066, 1950. 23 pp.; 3 tables; 13 figs.; Unc.

A method of relating the effects of fuel-air ratio on the knock-limited charge flow and power of a supercharged engine with those of compression ratio and inlet-air temperature is presented. These variables are correlated by means of a relation between knock-limited end-gas density and end-gas temperature calculated from engine-inlet conditions at incipient knock. Knock data obtained in a CFR engine over a wide range of conditions were correlated for the following eight fuels: 28-R fuel, aviation alkylate, S reference fuel, diisopropyl, triptane, cyclohexane, cyclopentane, and triptene. Charts are also presented by means of which knock-limited charge flow and indicated mean effective pressure may be determined for a fuel when its correlation curve is known.

When knock-limited charge flow calculated from the correlation curves was compared with experimentally determined charge flow for each fuel over many conditions, the smallest mean error was 2.7 percent for 28-R fuel and the largest mean error was 8.6 percent for triptane. The mean error in calculated charge flow for all the fuels at all the operating conditions investigated was 5.0 percent.

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E. Preignition

<u>Preignition-Limited Performance of Several Fuels.</u> By Donald W. Male and John C. Evvard. NACA Rep. 811, 1945. (Supersedes NACA ARR E5A11.) 5 pp.; 6 figs.; Unc. 2356

Preignition-limited performance data were obtained on a supercharged CFR engine at two sets of operating conditions over a wide range of fuel-air ratios to determine the preignition characteristics for the following five fuels: S-3 reference fuel, S-3 plus 4 ml TEL per gallon, AFD-33 (140-P), benzene, and diisobutylene. Maximum thermal-plug temperatures at constant intake-air pressures were also determined to correlate the preignition characteristics of each fuel with its ability to increase general engine-temperature levels. Additional runs were made to compare the preiginition-limited performance of triptane, triptane plus 4 ml TEL per gallon, and AN-F-28R fuel.

The results indicated that in the fuel-air ratio range from 0.070 to 0.085, the relative order of the fuels according to increasing preignition-limited indicated mean effective pressures was diisobutylene, benzene, S-3, AFD-33, and S-3 plus 4 ml TEL per gallon. The relative order of the fuels for the two sets of operating conditions was not the same for all fuel-air ratios. The addition of tetraethyl lead to either S-3 reference fuel or triptane raised the preignition-limited performance. The plot of fuel flow against air flow at the preignition limit for each fuel shows that the data approximately follow two straight lines: one for the rich-mixture region and one for the lean-mixture region. The respective slopes of these lines changed only slightly in the various preignition-limited runs.

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<u>The Effect of Engine Variables on the Preignition-Limited Performance of Three Fuels.</u> By Donald W. Male. NACA TN 1131, 1946. 7 pp.; 1 table; 18 figs.; Unc.

Preignition-limited performance data for S-reference fuel, diisobutylene, and benzene were obtained with an engine-heated hot spot on a supercharged CFR engine at 11 sets of engine operating conditions. Increases in compression ratio, spark advance, coolant temperature, or inlet-air temperature decreased the preignition-limited indicated mean effective pressure of all three fuels. Changes in the engine speed either raised or lowered the preignition-limited indicated mean effective pressure depending on the range of speed and the mixture strength. At nearly all of the operating conditions investigated, the order of the fuels according to increasing preignition-limited performance was the same, that is, diisobutylene, benzene, and S-reference fuel.

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Effect of Fuel Composition, Engine Operating Variables, and Spark-Plug Type and Condition on Preignition-Limited Performance of an R-2800 Cylinder. By John F. Pfender. NACA RM E6J08, 1946. 12 pp.; 4 tables; 11 figs.; Rest.

The preignition characteristics of the R-2800 cylinder, as affected by fuel composition, engine operating variables, and spark-plug type and condition, were evaluated. The effects on preignition-limited performance of various percentages of aromatics (benzene, toluene, cumene, and xylene) in a base fuel of triptane were investigated. Two paraffins (triptane and S + 6.0 ml TEL/gal) and two refinery blends (28-R and 33-R) were preignition-rated. The effect of changes in the following engine operating variables on preignition limit was determined: inlet-air temperature, rear-spark-plug-gasket temperature, engine speed, spark advance, tappet clearance, and oil consumption. Preignition limits of the R-2800 cylinder using Champion C34S and C35S and AC-LS86, LS87, and LS88 spark plugs were established and the effect of spark-plug deterioration was investigated.

No definite trends in preignition-limited indicated mean effective pressure were indicated for aromatics as a class when increased percentages of different aromatics were added to a base fuel of triptane. Three types of fuel (aromatics, paraffins, and refinery blends) showed a preignition range for this cylinder from 85 to 104 percent when based on the performance of S plus 6.0 ml TEL per gallon as 100 percent. The R-2800 cylinder is therefore relatively insensitive to fuel composition when compared to a CFR F-4 engine, which had a preignition range from 72 to 100 percent for the same fuels.

Six engine operating variables were investigated with the following results: preignition-limited indicated mean effective pressure decreased with increases in engine speed, rear-spark-plug-gasket temperature, inlet-air temperature, and spark advance beyond 20° B.T.C. and was unaffected by rate of oil consumption or by tappet clearance.

Spark plugs were rated over a range of preignition-limited indicated mean effective pressure from 200 to 390 pounds per square inch at a fuel-air ratio of 0.07 in the following order of increased resistance to preignition: AC-LS87, AC-LS88, Champion C35S, AC-LS86, and Champion C34S. Spark-plug deterioration in the form of cracks in the porcelain did not affect the preignition limit. When pieces of porcelain had been br... away from the center electrode and were retained in the spark-plug cavity, the preignition limit was decreased as much as 57 percent. When the broken pieces had been removed, the preignition limit increased from that of the undamaged porcelain as the weight of removed porcelain was increased.

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<u>Effect of Preignition on Cylinder Temperatures, Pressures, Power Output, and Piston Failures.</u> By Lester C. Corrington and William F. Fisher. NACA TN 1637, 1948. (Supersedes NACA RM E6L10.) 14 pp.; 15 figs.; Unc. 2956

An investigation using a cylinder of a V-type liquid-cooled engine was conducted to observe the behavior of the cylinder when operated under preignition conditions. The effects of the following variables were investigated: fuel-air ratio, power output, aromatic content of fuel, engine speed, mixture temperature, and preignition source. The power outputs at which preignition would cause complete piston failure for the selected engine operating conditions and the types of failure encountered when using various values of clearance between the piston and the cylinder barrel were determined.

The results indicate that in the engine investigated preignition at high power levels led to backfiring into the induction system under most conditions. Preignition caused cylinder-head temperatures to increase up to 200° F at rates up to 30° F per second, caused maximum cylinder pressures to increase up to 30 percent, and caused power output to be drastically reduced. Runs to destruction indicated that preignition caused overheating that resulted in overexpansion of the piston, seizure of the piston in the cylinder barrel, and consequent melting of the side of the piston. By increasing the clearance between the piston and the cylinder barrel it was possible to increase the power level at which piston failure occurred because of preignition.

The aromatic content of the fuel had only a small effect on the behavior of the engine after preignition was excited. The greatest effect was in the peak-pressure increase, the trend being toward a direct relation between aromatic content and peak-pressure increase.

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Cross Reference

<u>A Relation Between Knock-Limited or Preignition-Limited Air-Fuel Ratio at Lean Mixtures and Fuel-Air Ratio at Rich Mixtures.</u> By John C. Evvard. NACA WR E-208, 1945. (Supersedes NACA CB E5J11.) (<u>See I-D.</u>)

F. Vapor Loss

Reduction of Fuel-Vapor Loss by Omitting Some of the Fuel Constituents Normally Lost During Flight. By Charles S. Stone and Walter E. Kramer. NACA WR E-184, 1945. (Supersedes NACA MR E5H27.) 11 pp.; 9 figs.; Unc.

An investigation was conducted to determine the effect on fuel-vapor loss during flight of omitting in the blending process some of the fuel consitutuents in AN-F-28, Amendment-2, fuel that are normally lost in flight. In this particular series of tests, some of the lower-boiling-point components were removed from available AN-F-28, Amendment-2, fuel by means of a fractionating column.

The results show that the fuel-vapor loss for a given set of simulated-flight conditions decreased as the percentage of fuel removed increased. Also, the altitude at which fuel-vapor loss begins (critical altitude) was found to increase as the percentage of fuel removed increased. These relations were found to depend on the initial characteristics of the original fuel sample.

The Reid vapor pressure and the A.S.T.M. 5- and 10-percent recovered points gave single-valued functions with fuel-vapor loss and critical altitude. These physical properties as indicated by data for AN-F-28, Amendment-2, fuel may be used to determine the extent of omission necessary to prevent fuel-vapor loss for a given set of flight conditions.

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Effects of Fuel-Vapor Loss on Knock-Limited Performance and Inspection Properties of Aviation Fuels. By Henry C. Barnett and Eldred T. Marsh. NACA WR E-221, 1946. (Supersedes NACA RB E6C01.) 4 pp.; 1 table; 5 figs.; Unc.

Past experience has shown that, at certain temperature conditions, the fuel in the tank of an airplane loses a portion of the lower boiling-point components when the airplane rises to altitude. The investigation reported herein was conducted specifically to ascertain the effects of this fuel-vapor loss on the F-3 and F-4 knock-limited performance ratings and the inspection properties of two representative aviation fuels. Fuels meeting AN-F-28 and AN-F-33 aviation fuel specifications were used, 28-R and 33-R, respectively.

Weathering tests made on samples of 28-R and 33-R aviation fuels under simulated-flight conditions consisting of a climb at a rate of 1000 feet per minute to an altitude of 30,000 feet with this altitude maintained for 10 minutes after the end of the climb showed that:

1. (a) For an initial fuel temperature of 90° F the loss (by weight) resulting from weathering 28-R fuel was 3.6 percent; for 33-R fuel the loss was 3.5 percent.

(b) For an initial fuel temperature of 130° F the weathering loss for 28-R fuel was 12.8 percent; for 33-R fuel the loss was 14.4 percent.

2. (a) Inspection data for samples of 28-R and 33-R fuels showed that these fuels weathered from an initial temperature of 90° F meet current Army-Navy fuel specifications for fuels of these grades, except for high tetraethyl lead concentrations. 2956

(b) For an initial temperature of 130° F the weathered sample of 28-R fuel meets specification requirements with the exception of a high tetraethyl lead concentration, whereas the weathered sample of 33-R fuel is not acceptable because of the high 50-percent distillation point as well as a high tetraethyl lead concentration.

3. The F-3 and F-4 antiknock ratings for the weathered fuel samples showed little or no change resulting from loss of some of the lighter ends due to weathering. The small changes found indicate that the weathered samples have slightly higher ratings than the unweathered samples.

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G. Internal Coolants

Knock-Limited Performance of Several Internal Coolants. By Donald R. Bellman and John C. Evvard. NACA Rep. 812, 1945. (Supersedes NACA ACR 4B08.) 13 pp.; 8 figs.; Unc.

The effect of internal cooling on the knock-limited performance of AN-F-28 fuel was investigated in a CFR engine, and the following internal coolants were used: (1) water, (2) methyl alcohol - water mixture, (3) ammonia - methyl alcohol - water mixture, (4) monomethylamine-water mixture, (5) dimethylamine-water mixture, and (6) trimethylamine-water mixture. The internal coolants were injected in the ratio of 1/2 pound per pound of AN-F-28 fuel. Tests were run at inlet-air temperatures of 150° and 250° F to indicate the temperature sensitivity of the internal-coolant solutions.

In this investigation the use of methyl alcohol - water, monomethylamine-water, and dimethylamine-water mixtures as internal coolants raised the knock limit more than did water alone. The addition of ammonia to the methyl alcohol - water mixture lowered its knock-inhibiting effects. For most fuel-air ratios, the trimethylamine-water mixture decreased the knock-limited power.

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Effect of Water-Alcohol Injection and Maximum-Economy Spark Advance on Knock-Limited Performance and Fuel Economy of a Large Air-Cooled Cylinder. By Jack E. Vandeman and Orville H. Heinicke. NACA WR E-264, 1945. (Supersedes NACA MR E5H12.) 7 pp.; 5 figs.; Unc.

An investigation was conducted to determine the effect of a coolant solution of 25 percent ethyl alcohol, 25 percent methyl alcohol, and 50 percent water by volume and maximum-economy spark advance on knock-limited performance and fuel economy of a large air-cooled cylinder. 2956 The knock-limited performance of the cylinder at engine speeds of 2100 and 2500 rpm was determined for coolant-fuel ratios of 0.0, 0.2, and 0.4. The effect of water-alcohol injection on fuel economy was determined in constant charge-air flow tests. The tests were conducted at a spark advance of 20° B.T.C. and maximum-economy spark advance.

The following results were obtained:

1. The knock-limited power at an engine speed of 2100 rpm was increased as much as 88 percent by operation at a fuel-air ratio of 0.060 and a coolant-fuel ratio of 0.4.

2. An increase in the coolant-fuel ratio from 0.2 to 0.4 was 2.5 times as effective in raising the knock-limited indicated mean effective pressure at a fuel-air ratio of 0.075 as an increase in the coolant-fuel ratio from 0.0 to 0.2.

3. The indicated specific liquid consumption was less with a coolant-fuel ratio of 0.4 than with fuel alone for power levels above a knock-limited indicated mean effective pressure of 225 pounds per square inch at an engine speed of 2500 rpm.

4. When the spark advance was increased from 20° B.T.C. to maximum-economy spark advance at a fuel-air ratio of 0.060, the indicated specific fuel consumption was decreased 4 percent in constant charge-air flow tests and the knock-limited indicated mean effective pressure was decreased 21 percent.

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Effect of Internal Coolants on the Knock-Limited Performance of a Liquid-Cooled Multicylinder Aircraft Engine with a Compression Ratio of 6.0. By R. Lee Nelson, Myron L. Harries, and Rinaldo J. Brun. NACA WR E-260, 1945. (Supersedes NACA MR E5F30.) 12 pp.; 1 table; 9 figs.; Unc.

An investigation was conducted to determine the effect of internal coolants on the knock-limited performance of a liquid-cooled multicylinder aircraft engine with a displacement of 1710 cubic inches and a compression ratio of 6.0. Knock-limited performance tests were conducted at an engine speed of 3000 rpm, fuel-air ratios from 0.075 to 0.085, carburetor-air temperatures of 120° and 60° F, and with water and water-ethanol as internal coolants. Each internal coolant was injected in turn through the fuel-spray nozzle and through intake-manifold spray jets. All tests were conducted with 28-R fuel.

The following results were obtained:

1. The maximum knock-limited brake horsepower attained was 2310 at a fuel-air ratio of 0.079 and a carburetor-air temperature of 60° F with 663 pounds per hour of water-ethanol introduced with the fuel through the fuel-spray nozzle.

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2. In general, at low internal-coolant flows or at the high carburetor-air temperature, water was more effective than water-ethanol in raising the knock-limited brake horsepower. As the internal-coolant flow was increased or the carburetor-air temperature decreased, water-ethanol became more effective than water.

3. Fuel-nozzle injection of a given internal coolant at a given carburetor-air temperature was generally more effective in raising the knock-limited brake horsepower than injection through intake-manifold spray jets.

4. Except at some of the lower internal-coolant flows, a higher manifold pressure was required to obtain a given knock-limited brake horsepower by means of internal-coolant injection than by means of lowering the carburetor-air temperature.

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Knock-Limited Power Outputs from a CFR Engine Using Internal Coolants. II - Six Aliphatic Amines. By Donald R. Bellman, W. E. Moeckel, and John C. Evvard. NACA WR E-219, 1945. (Supersedes NACA ACR E5H31.) 8 pp.; 1 table; 4 figs.; Unc.

An investigation was conducted to determine the knock-limited performance of AN-F-28, Amendment-2, fuel in a CFR engine when water solutions of the following aliphatic amines were added as internal coolants: monomethylamine, dimethylamine, ethylenediamine, diethylamine, triethylamine, and butylamine. All of the internal-coolant solutions consisted of 25 percent amine and 75 percent water except for monomethylamine and dimethylamine solutions, which had a slightly higher percentage of amine. The internal coolant-fuel ratio was 0.50 in most cases, but tests were run using water and water solutions of dimethylamine at a coolant-fuel ratio of 0.75. Comparison curves were run with no internal coolant and with water alone as an internal coolant. Experiments were conducted to determine the effect of increases in fuel flow and internal-coolant flow at constant air flow on the power output when the engine was operating at a high power level by means of the injection of dimethylamine-water solution.

For fuel-air ratios between 0.055 and 0.095, the addition of the diethylamine, triethylamine, and butylamine solutions decreased the knock-limited power. A knock-limited indicated mean effective pressure of 1024 pounds per square inch was obtained at a fuel-air ratio of 0.093 when using the dimethylamine-water solution at a coolant-fuel ratio of 0.75.

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Knock-Limited Power Outputs from a CFR Engine Using Internal Coolants. III - Four Alkyl Amines, Three Alkanolamines, Six Amides, and Eight Heterocyclic Compounds. By Harry S. Imming and Donald R. Bellman. NACA RM E6L05a, 1947. 7 pp.; 1 table; 5 figs.; Unc.

Investigations were conducted to determine the antiknock effectiveness of various additive-water solutions used as internal coolants in conjunction with AN-F-28, Amendment-2, fuel in a modified CFR engine. Each internal-coolant solution was injected at a coolant-fuel ratio of 0.50 and contained 70-percent water and 30-percent by weight of each of the following compounds:

- Alkyl amines
  - Isopropylamine
  - Isobutylamine
  - *tert*-Butylamine
  - Monoamylamine
- Alkanolamines
  - Ethanolamine
  - Diethanolamine
  - 2-Amino-2-methyl-1-propanol
- Amides
  - Formamide
  - N-Ethylformamide
  - N-Ethylacetamide
  - N-Ethylpropionamide
  - N,N-Dimethylformamide
  - N,N-Diethylacetamide
- Heterocyclic compounds
  - 2,2-Dimethylethylenimine
  - Morpholine
  - Pyridine
  - 2-Methylpyridine
  - 3-Methylpyridine
  - 4-Methylpyridine
  - 2,6-Dimethylpyridine
  - 2-Vinylpyridine

Results of investigations are also presented for AN-F-28, Amendment-2, fuel run with no internal coolant and with water alone as the internal coolant at coolant-fuel ratios of 0.35 and 0.50. Three of the alkyl amines, the six amides, and six of the heterocyclic compounds raised the knock limit of the base fuel more than an equivalent amount of water at most of the fuel-air ratios investigated. Ethanolamine and 2-amino-2-methyl-1-propanol raised the knock limit more than an equivalent amount of water at fuel-air ratios greater than 0.093. The 21 compounds investigated were less effective in raising the knock limit than monomethylamine, dimethylamine, and ethylenediamine, which were previously investigated. 2356

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<u>Nitrous Oxide Supercharging of an Aircraft-Engine Cylinder.</u> By Max J. Tauschek, Lester C. Corrington, and Merle C. Huppert. NACA WR E-199, 1945. (Supersedes NACA MR E5F26.) 16 pp.; 3 tables; 15 figs.; Unc.

An investigation was made to determine the performance of an aircraft-engine cylinder using nitrous oxide to provide additional supercharging. Single-cylinder tests were conducted at constant manifold pressure in which nitrous oxide was added as a gas to the inlet air to provide extra supercharging. Determinations were made of the effects of this method of supercharging on power output, cylinder-head temperature, and fuel consumption; and an evaluation was made of methods of cooling the cylinder when using nitrous oxide. Additional tests were conducted to find the effects of nitrous oxide supercharging on the knock-limits when using 28-R and 33-R fuels. Calculations were made using these data to estimate the effect on engine performance of injecting the nitrous oxide into the induction system as a liquid.

The results of the tests and calculations are summarized as follows:

Injection as a gas (test results):

1. With constant manifold pressure, the nitrous oxide increased the power output about 14 percent on an indicated basis at a nitrous oxide-air ratio of 0.1; this increase amounted to about 25 percent at a ratio of 0.2.

2. The knock-limited power output was increased about 9 percent on an indicated basis with a nitrous oxide-air ratio of 0.1 and about 17 percent with a nitrous oxide-air ratio of 0.2. The knock-limited manifold pressure was decreased about 2 percent and 4 percent, respectively, for these ratios.

3. Increasing the oxygen concentration in the charge by the addition of nitrous oxide increased the flame speed, resulting in decreased values of optimum spark timing. This effect was especially notable at extremely rich fuel-oxygen ratios.

4. The use of nitrous oxide resulted in abnormally high cylinder-head temperatures. When knock is not a limitation, these temperatures can be controlled to best advantage by the use of mixture enrichment. When knock is a limitation, the use of water or water-alcohol injection may be preferable.

Injection as a liquid at -128° F (calculated results):

1. The nitrous oxide would lower the inlet-mixture temperature to such an extent when injected as a liquid that poor mixture distribution may result unless special means are provided to prevent this difficulty. When mixture distribution is not a problem, calculations indicate that the liquid nitrous oxide would increase the indicated power output about twice as much as with gaseous injection for a given manifold pressure.

2. Calculations and test data show that the lowered mixture temperatures brought about by injection of nitrous oxide as a liquid should cause the knock-limited indicated power output to be somewhat lower than that obtained with gaseous injection at a fuel-oxygen ratio of 0.410. At richer fuel-oxygen ratios, however, the knock-limited power was increased as the mixture temperature was lowered.

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II. TURBOJET ENGINE FUEL

A. Combustion Efficiency and Altitude Performance

1. Boiling Range and Composition

Effect of Fuel on Performance of a Single Combustor of an I-16 Turbojet Engine at Simulated Altitude Conditions. By Eugene V. Zettle, Ray E. Bolz, and R. T. Dittrich. NACA RM E7A24, 1947. 7 pp.; 1 table; 2956
11 figs.; Unc.

As part of a study of the effects of fuel composition and volatility on the combustor performance of a turbojet engine, an investigation was made in a single I-16 combustor with the standard I-16 injection nozzle, supplied by the engine manufacturer, at simulated altitude conditions.

The 10 fuels investigated included hydrocarbons of the paraffin olefin, naphthene, and aromatic classes having a boiling range from 113° to 655° F. They were hot-acid octane, diisobutylene, methylcyclohexane, benzene, xylene, 62-octane gasoline, kerosene, solvent 1, solvent 2, and Diesel fuel oil. The fuels were tested at combustor conditions simulating I-16 turbojet operation at an altitude of 45,000 feet and at a rotor speed of 12,200 rpm. At these conditions the combustor-inlet air temperature, static pressure, and velocity were 60° F, 12.3 inches of mercury absolute, and 112 feet per second, respectively, and were held approximately constant for the investigation. The reproducibility of the data is shown by check runs taken each day during the investigation. The combustion in the exhaust elbow was visually observed for each fuel investigated.

When no attempt was made to adjust the fuel-spray-tip design to compensate for differences in the properties of the fuels, the combustion efficiency of the combustor decreased with an increase in fuel boiling point, particularly in the range of low heat inputs. The efficiency was relatively unaffected by differences in the hydrocarbon type for the fuels investigated except for aromatic fuels, which exhibited somewhat lower efficiencies than the other classes.

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Fuel Tests on an I-16 Jet-Propulsion Engine at Static Sea-Level Conditions. By Ray E. Bolz and John B. Meigs. NACA RM E7B01, 1947. 6 pp.; 1 table; 15 figs.; Rest.

The effect of fuel composition and boiling point on the performance of the type I-16 jet-propulsion engine was investigated.

Tests were made on 14 fuels embodying different types of hydrocarbon and having boiling points lying within the range of 150° to 650° F. Each fuel was tested in an I-16 engine at static sea-level conditions at 13 rotor speeds varying from 11,000 to 16,500 rpm. Performance was based on speed, thrust, fuel flow, air flow, tail-pipe temperature and pressure, and temperature rise and pressure drop across the combustion chamber.

The following results were obtained for the I-16 engine tested at static sea-level conditions:

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Fuel composition and boiling range have a negligible effect upon engine thrust, rotor speed, and gas temperatures for the principal types of hydrocarbon fuel when used for short periods of time. The effect of fuel types on the performance and reliability of the engine over long periods of operation was not determined. Operation of the engine using fuels containing very high percentages of aromatics and olefins resulted in visible black smoke in the exhaust gases. The smoke from the aromatics was much more dense than that resulting from the olefinic fuel.

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<u>Combustion-Efficiency Investigation of Special Fuels in Single Tubular-Type Combustor at Simulated Altitude Conditions.</u> By Ralph T. Dittrich. NACA RM E7F11, 1947. 7 pp.; 2 tables; 8 figs.; Rest.

A combustion-efficiency investigation of 10 special straight-run distillate fuels was conducted in an individual tubular-type combustor unit of a 14-unit assembly at two simulated engine operating conditions. These distillates were obtained from various crude oils and consisted of hydrocarbon mixtures with distillation temperature varying from 93° to 690° F. Three commercial fuels were also tested, one of which was used for checking reproducibility. The operating conditions simulated engine operation at an altitude of 40,000 feet at engine speeds of 7000 and 10,500 rpm.

Comparison of temperature measurements obtained from two locations in the exhaust duct showed that under certain operating conditions the flame extended beyond the turbine position.

The data obtained in these fuel tests showed that as the distillation temperature of the fractions from the same crude increased, the combustion efficiency decreased. Correlations are shown of combustion efficiency with the 50-percent boiling point, with viscosity, and with an empirical function of the 50-percent boiling point and specific gravity.

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Fuel Investigation in a Tubular-Type Combustor of a Turbojet Engine at Simulated Altitude Conditions. By Adelbert O. Tischler and Ralph T. Dittrich. NACA RM E7F12, 1947. 12 pp.; 2 tables; 27 figs.; Rest.

As part of a preliminary study of fuels for turbojet engines, a series of 11 fuels, which ranged in volatility from gasoline to Diesel oil and which included hydrocarbons of the paraffinic, naphthenic, olefinic, and aromatic types, was tested in a single tubular combustor chamber of a turbojet engine under inlet-air conditions that simulated engine operation at two engine speeds at an altitude of 40,000 feet. 2956
Tests were also conducted at two additional inlet-air conditions. Temperature-rise data at various fuel-air ratios were obtained for each set of air-flow conditions. No variations in combustor geometry or fuel nozzle were made in this investigation.

At the three most severe operating conditions, it was found that combustion efficiencies obtained with various fuels decreased as the boiling temperatures of the fuels increased. At inlet-air conditions simulating engine operation at an altitude of 40,000 feet and an engine speed of 10,500 rpm, the differences in combustion efficiencies for fuels of different boiling points, however, were insignificant.

For fuels boiling within the gasoline boiling range, the hydrocarbon type of the fuel was observed to have only a small effect on the combustion efficiencies. In general, the combustion efficiencies appeared to decrease as the degree of unsaturation of the hydrocarbon increased.

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Combustion-Efficiency and Altitude-Limit Investigations of Five Fuels in an Annular Turbojet Combustor. By Jerrold D. Wear and Edmund R. Jonash. NACA RM E7L30, 1948. 9 pp.; 19 figs.; Rest.

Five fuels of various boiling temperatures and various hydrocarbon types were investigated in a jet-propulsion annular combustor of $10\frac{3}{8}$-inch diameter to determine the effect of fuel boiling temperature and paraffinic and aromatic hydrocarbon types on combustion efficiency and altitude operational limit.

The fuels used in this investigation were commercial isoheptane, AN-F-28R, AN-F-32, benzene, and aromatic solvent. Commercial isoheptane, AN-F-28R, and AN-F-32 were considered paraffinic fuels with low, medium, and high boiling temperatures, respectively. Benzene and aromatic solvent were considered aromatic fuels with low and high boiling temperatures, respectively.

At the severe inlet-air condition (unstable combustion), the highest combustion efficiencies were obtained with the paraffinic and aromatic fuels with low boiling temperatures (isoheptane and benzene) and were found to vary from 30 to 58 percent. At the moderate inlet-air condition (intermediately stable combustion), the paraffinic fuels with low and medium boiling temperatures (isoheptane and AN-F-28R) gave the highest combustion efficiencies, which varied from 70 to 95 percent. The maximum variation of altitude operational limit among the fuels was 5000 feet.

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<u>Performance Investigation of Can-Type Combustor. I - Instrumentation, Altitude Operational Limits and Combustion Efficiency.</u> By Eugene V. Zettle and William P. Cook. NACA RM E8F17, 1948. 5 pp.; 1 table; 21 figs.; Rest.

A brief investigation of the performance of a single can-type combustor designed for a turbojet engine having a military rating of 4000 pounds thrust at a rotor speed of 7700 rpm and equipped with an 11-stage axial-flow compressor and a single-stage turbine has been made. The investigation was conducted to determine: (a) the altitude operational limits of the engine for two fuels (AN-F-32 and AN-F-28), (b) combustion efficiencies at various simulated conditions of altitude and engine speed, (c) combustor-outlet temperature distribution for several altitudes at constant engine speed, and (d) the combustor total-pressure drop.

The limits with AN-F-32 fuel were found to be approximately 60,000 feet for an engine speed of 6000 rpm and approximately 38,000 feet for an engine speed of 4000 rpm. The results indicated that the altitude operational limits with AN-F-32 fuel are higher over the largest part of the engine-speed range than with AN-F-28 fuel. A combustion efficiency of 95 percent was obtained at rated engine speed (7600 rpm) and an altitude of 20,000 feet with AN-F-32 fuel. A change in altitude from 20,000 to 60,000 feet showed a 20-percent decrease in combustion efficiency while the engine was operating at 7600 rpm; whereas, at an engine speed of 4000 rpm a change of altitude from 10,000 to 40,000 feet showed a 52-percent decrease in combustion efficiency.

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<u>Turbojet Combustor Efficiency at High Altitudes.</u> By Walter T. Olson, J. Howard Childs, and Edmund R. Jonash. NACA RM E50I07, 1950. 21 pp.; 28 figs.; Conf.

NACA research on the single problem of combustion efficiency of turbojet engines at high altitudes is discussed. Representative results of investigations with turbojet combustors are presented to illustrate the trends obtained with the following categories of variables: (1) combustor operating variables, (2) combustor design variables, and (3) fuel variables.

The data indicated that as the environment of the combustor becomes one of low pressure and low temperature at high altitude, low combustion efficiencies and limited values of obtainable temperature rise were encountered. Increased cross-sectional area of combustor for a given weight flow of air decreased velocities and facilitated high combustion efficiency at altitude. For the design of the liner, increased volume in the flame zone and gradual admission of the air into the combustion space were shown to aid combustion by helping to provide localized fuel-air mixtures of correct composition that exist sufficiently long for ignition and combustion to occur. For high combustion efficiency to occur, all the fuel must be involved in this manner, and it was shown that the combustor design, the fuel injection, and the fuel volatility must be matched if optimum combustion efficiency is to be achieved; in general, combustion efficiency decreased with increased fuel boiling temperatures. Further, it was shown that fuels of higher flame speed and/or lower ignition temperatures gave higher combustion efficiency when other properties were similar.

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Factors in Selecting Fuels for Gas-Turbine Powered Aircraft. By Louis C. Gibbons. NACA RM E50I18, 1950. 33 pp.; 2 tables; 48 figs.; Conf.

This report briefly summarizes some of the available information on fuels for gas-turbine powered aircraft. Included are discussions on fuel availability, heat energy, vapor loss, aerodynamic heating, combustion efficiency, operational limits, carbon deposits, pumping, storage, and fire hazard.

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Performance of Pure Fuels in a Single J33 Combustor. I - Five Liquid Hydrocarbon Fuels. By Jerrold D. Wear and Ralph T. Dittrich. NACA RM E52J03, 1952. 12 pp.; 2 tables; 17 figs.; Conf.

Investigations of several pure hydrocarbon fuels were conducted in a single tubular-type combustor in order to determine possible relations between combustor performance and fuel properties. The combustor temperature rise, combustion efficiency, and blow-out limits were determined with five liquid hydrocarbon fuels of high purity over a range of heat input and air-flow rates and at two inlet-air-temperature conditions. The fuels were isooctane, cyclohexane, methylcyclohexane, n-heptane, and benzene. Performance parameters were selected to compare with the physical and fundamental combustion properties of the fuel.

The general performance order among the fuels was: benzene highest; isooctane lowest; cyclohexane, methylcyclohexane, and n-heptane intermediate. Of the several fuel properties considered, maximum burning velocity best correlated with fuel performance, indicating an approximately linear increase in the performance of the fuels with an increase in burning velocity. For the various test conditions investigated, the maximum combustor temperature rise and the combustion efficiencies increased by 230° to 400° F and 2 to 17 percent for an increase in maximum burning velocity from 34.6 to 40.7 centimeters per second.

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Cross References

Effect of Fuels and Fuel-Nozzle Characteristics on Performance of an Annular Combustor at Simulated Altitude Conditions. By Richard J. McCafferty. NACA RM E8C02a, 1948. (See II-A-4.)

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Altitude Performance of AN-F-58 Fuels in British Rolls-Royce Nene Single Combustor. By William P. Cook and Richard G. Koch. NACA RM E9D08, 1949. (See II-A-2.)

Investigation of Altitude Performance of AN-F-58 Fuels in Annular Combustor of J34-WE-22 Engine. By Adelbert O. Tischler and Wilfred E. Scull. NACA RM E9A31, 1949. (See II-A-2.)

Altitude Performance of AN-F-58 Fuels in J33-A-21 Single Combustor. By Ralph T. Dittrich and Joseph L. Jackson. NACA RM E8L24, 1949. (See II-A-2.)

Altitude Performance of AN-F-58 Fuels in J35-C-3 Single Combustor. By Edward G. Stricker and Warren D. Rayle. NACA RM E8L20a, 1949. (See II-A-2.)

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2. JP-1 and JP-3 Fuel

Comparison of Performance of AN-F-58 and AN-F-32 Fuels in J33-A-23 Turbojet Engine. By H. D. Wilsted and J. C. Armstrong. NACA RM E8K24, 1949. 10 pp.; 1 table; 13 figs.; Rest.

As part of an extensive evaluation program to determine the comparative performance of fuels conforming to specifications AN-F-58 and AN-F-32, an investigation was conducted in an altitude chamber using a 4600-pound-thrust turbojet engine.

In comparison with the performance of AN-F-32 fuel, AN-F-58 had the following characteristics:

(1) Equal performance with AN-F-32 fuel in terms of engine thrust and fuel consumption

(2) Improved altitude starting characteristics

(3) Less tendency for blow-out at low engine speeds

(4) Higher carbon-deposition rate that, however, did not appear detrimental to engine performance 2956

(5) Contamination with iron oxide particles. These particles probably were held in suspension because of rapid handling of the fuel.

Within the limits of this investigation, AN-F-58 fuel was essentially equal in performance and in some respects had improved performance as compared with AN-F-32 fuel. The AN-F-58 fuel is therefore considered satisfactory for service flight tests in the engine used.

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<u>Altitude Performance of AN-F-58 Fuels in British Rolls-Royce Nene Single Combustor.</u> By William P. Cook and Richard G. Koch. NACA RM E9D08, 1949. 8 pp.; 1 table; 8 figs.; Conf.

An investigation was conducted with a single combustor from a British Rolls-Royce Nene turbojet engine to determine the altitude performance characteristics of AN-F-58 fuels. Three fuel blends conforming to AN-F-58 specifications were prepared in order to determine the influence of fuel boiling temperatures and aromatic content on combustion efficiencies and altitude operational limits. The performance of the three AN-F-58 fuels was compared in the range of altitudes from sea level to 65,000 feet, engine speeds from 40 to 100 percent normal rated, and flight Mach numbers of 0 and 0.6. Similar information was obtained for AN-F-32 fuel at a flight Mach number of 0.

The altitude operational limits of the three AN-F-58 fuels were the same at rated speed and flight Mach numbers of 0 and 0.6. The high-aromatic AN-F-58 fuel gave altitude limits below those of the base-stock and high-end-point AN-F-58 fuels at lower engine speeds, being about 10,000 feet (flight Mach number, 0) and 5000 feet (flight Mach number, 0.6) lower at 70 percent normal rated engine speed. The altitude operational limits of AN-F-32 fuel were about the same as those for the base-stock and high-end-point AN-F-58 fuels at a flight Mach number of 0.

The combustion efficiencies with the four fuels ranged from 54.5 to 100 percent with the higher efficiencies occurring at low altitudes and high engine speeds. Although the scatter of data was large, some indication existed that combustion efficiencies with the high-aromatic fuel decreased more rapidly than the other fuels as the engine speed was decreased and as the altitude was increased.

Carbon deposition during operation with the three AN-F-58 fuels was slight.

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<u>Investigation of Altitude Performance of AN-F-58 Fuels in Annular Combustor of J34-WE-22 Engine.</u> By Adelbert O. Tischler and Wilfred E. Scull. NACA RM E9A31, 1949. 8 pp.; 2 tables; 7 figs.; Conf.

An investigation was conducted in the combustor of a 3000-pound-thrust turbojet engine to determine the altitude performance characteristics of AN-F-58 fuels. Three fuels conforming to AN-F-58 specification were prepared in order to determine the influence of boiling temperature range and aromatic content on altitude performance. The performance of the three AN-F-58 fuels was compared with the performance of AN-F-48 (grade 100/130) fuel in the range of simulated altitudes from 20,000 to 55,000 feet, corrected engine speeds from 6000 to 12,500 rpm, and flight Mach numbers of 0.2 and 0.6.

At a flight Mach number of 0.2, the altitude limits of two AN-F-58 fuels were the same and about 1000 to 3000 feet higher than the limits of AN-F-48 fuel over the range of engine speeds examined. The altitude operational limit of the AN-F-58 fuel having a higher boiling-temperature range and a higher aromatic content than the other two AN-F-58 fuels was 1000 to 7000 feet lower than the limits of the other two AN-F-58 fuels over the range of engine speeds investigated. At a Mach number of 0.6, the altitude limits of the three AN-F-58 fuels and the AN-F-48 fuel were approximately the same.

At any fixed operating condition, the combustion efficiency decreased as the volumetric average boiling temperature of the fuel increased. The arithmetical differences in combustion efficiency between the most volatile fuel (AN-F-48) and the least volatile AN-F-58 fuel were as great as 12 to 14 percent at some conditions near the altitude operational limit.

Light deposits of carbon were found with two AN-F-58 fuels and no deposits were found with the AN-F-48 fuel. The third AN-F-58 fuel having a high boiling-temperature range and high aromatic content produced formations of carbon on the first step of the combustor basket. These deposits, although not considered sufficiently large to be objectionable, were considerably greater than the deposits obtained with the other fuels.

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<u>Altitude Performance of AN-F-58 Fuels in J33-A-21 Single Combustor.</u> By Ralph T. Dittrich and Joseph L. Jackson. NACA RM E8L24, 1949. 7 pp.; 2 tables; 6 figs.; Rest.

An investigation was conducted in a single combustor from a 4600-pound-thrust turbojet engine to determine the altitude performance characteristics of AN-F-58 fuel. Three fuel blends conforming to the AN-F-58 specification were prepared in order to determine the influence of fuel boiling temperatures and aromatic content on altitude performance. The performance of the three AN-F-58 fuels was compared with the performance of AN-F-32 fuel in the range of altitudes from 5000 to 60,000 feet, engine speeds from 50 percent normal rated speed to military rated speed, and flight Mach numbers of 0 and 0.6. 2956

The combustion efficiencies of three AN-F-58 fuels and AN-F-32 fuel were approximately equal up to altitudes of about 50,000 feet. At higher altitudes some differences occurred. At an altitude of 60,000 feet, 90 percent normal rated engine speed, and a flight Mach number of 0.6, a maximum arithmetical difference among the fuels of 14 percent occurred. The effects of fuel boiling temperature, as represented by a comparison of two AN-F-58 fuels differing in final boiling temperature by 30° F (560° to 590° F), on combustion efficiency were found to be negligible even at the high altitudes. At the high-altitude condition, the combustion efficiency of a high-end-point, high-aromatic AN-F-58 fuel was greater than that of the high-end-point, low-aromatic AN-F-58 fuel, the differences being more marked at a flight Mach number of 0.6 than at a flight Mach number of 0. These differences cannot be attributed solely to a change in aromatic content inasmuch as the boiling temperatures in the middle distillation range of the two fuels also differ.

Although the altitude-operational-limit data are rather inconclusive, the operable speed range apparently tends to increase as the fuel boiling temperatures in the middle of the distillation range are increased.

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<u>Altitude Performance of AN-F-58 Fuels in J35-C-3 Single Combustor.</u> By Edward G. Stricker and Warren D. Rayle. NACA RM E8L20a, 1949. 8 pp.; 2 tables; 5 figs.; Rest.

An investigation was conducted in a single combustor of a 4000-pound-thrust turbojet engine to determine the altitude performance characteristics of AN-F-58 fuels. Three fuel blends conforming to AN-F-58 specification were prepared in order to determine the influence of fuel boiling temperature and aromatic content on combustion efficiency and altitude operational limits. The performance of the three AN-F-58 fuel blends was compared with the performance of AN-F-32 fuel in the range of altitudes from 20,000 to 60,000 feet, engine speeds from 39 to 104 percent normal rated speed, and flight Mach numbers of 0 and 0.6.

The effects of fuel boiling temperatures, as represented by comparison of two AN-F-58 fuel blends differing in final boiling temperature by 30° F (560° to 590° F), on combustion efficiency were found to be negligible. Comparison of a low-aromatic high-end-point AN-F-58 fuel with high-aromatic high-end-point AN-F-58 fuel indicated that for flight Mach numbers of 0 and 0.6 at 85 percent normal rated engine speed the variation in aromatic content and boiling temperature represented by the two fuels had a negligible effect on combustion efficiency. At 52 percent normal rated speed, however, the high-aromatic high-end-point AN-F-58 fuel gave lower combustion efficiencies than the low-aromatic high-end-point fuel especially at high altitudes. These results cannot be attributed solely to aromatic content because these two fuels also differed in boiling temperature in the middle distillation range. At the conditions investigated, the combustion efficiencies of AN-F-32 fuel were, in general, about the same as those for the high-aromatic high-end-point AN-F-58 fuel.

Comparisons among three AN-F-58 fuel blends and one AN-F-32 fuel did not show any consistent trends in altitude operational limits that might be attributed to either boiling temperatures or aromatic content.

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Altitude-Wind-Tunnel Investigation of AN-F-58 Fuel in Experimental Version of J47 Turbojet Engine. By Carl L. Meyer. NACA RM E8L13, 1949. 10 pp.; 1 table; 4 figs.; Conf.

An investigation was conducted in the NACA Lewis altitude wind tunnel to evaluate the performance of AN-F-58 fuel and, for comparative purposes, AN-F-32 fuel in an experimental turbojet engine. Data were obtained for a range of altitude, flight Mach number, and engine-speed conditions.

Combustion efficiencies obtained with AN-F-58 and AN-F-32 fuels were approximately equal; AN-F-58 combustion efficiencies were slightly higher than those for AN-F-32 fuel at the high altitudes and low flight Mach number. The effects of the fuels on other engine performance variables could not be determined because engine deterioration, accelerated by operation at severe engine conditions for a considerable length of time, made direct comparisons impossible. The minimum-speed altitude operational limit was essentially the same for the two fuels. The starting characteristics of the two fuels were approximately the same at the low windmilling speeds. Visual observation showed no apparent difference in the carbon-deposition rates of the two fuels.

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Comparison of Performance of AN-F-58 Fuel and Gasoline in J34-WE-22 Turbojet Engine. By Harry W. Dowman and George G. Younger. NACA RM E8L10a, 1949. 12 pp.; 2 tables; 11 figs.; Conf.

As part of an investigation of the performance of AN-F-58 fuel in various types of turbojet engine, the performance of this fuel in a 3000-pound-thrust turbojet engine has been investigated in an altitude test chamber together with the comparative performance of 62-octane gasoline.

The investigation of normal engine performance, which covered a range of engine speeds at altitudes from 5000 to 50,000 feet and flight Mach numbers up to 1.00, showed that both the net thrust and average turbine-outlet temperatures were approximately the same for both fuels. The specific fuel consumption and the combustion efficiency at the maximum engine speeds investigated were approximately the same for both fuels at altitudes up to 35,000 feet, but at an altitude of 50,000 feet the specific fuel consumption was about 9 percent higher and the combustion efficiency was correspondingly lower with the AN-F-58 fuel than with gasoline. The low-engine-speed blow-out limits were about the same for both fuels. Ignition of AN-F-58 fuel with the standard spark plug was possible only with the spark plug in a clean condition; ignition was impossible at all flight conditions investigated when the plug was fouled by an accumulation of liquid fuel from a preceding false start. Use of an extended-electrode spark plug provided satisfactory ignition over a slightly smaller range of altitudes and flight Mach numbers than for gasoline with the standard spark plug.

Radial temperature gradients at the turbine outlet were about the same for both fuels at an altitude of 20,000 feet. At an altitude of 50,000 feet, the difference in average temperature between the blade tip and the root was about 240° F greater for AN-F-58 fuel than for gasoline and the spread between the maximum and minimum temperatures at a given radial location was from 150° to 300° F less for AN-F-58 fuel than for gasoline. After 30 hours and 11 minutes of operation with AN-F-58 fuel, 240 grams of hard carbon deposits were built up on the combustor basket near the fuel nozzles.

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Comparison of Flight Performance of AN-F-58 and AN-F-32 Fuels in J35 Turbojet Engine. By Loren W. Acker and Kenneth S. Kleinknecht. NACA RM E8L02, 1949. 5 pp.; 2 tables; 6 figs.; Rest.

A flight investigation was conducted to determine the comparative performance of AN-F-58 and AN-F-32 fuels in a 4000-pound-thrust turbojet engine.

The results indicate that the performance of AN-F-58 fuel was equivalent to that of AN-F-32 fuel over the range of conditions investigated. The investigation of AN-F-58 fuel, compared with that of AN-F-32 fuel, indicated a 3-percent-higher net thrust and fuel consumption (same specific fuel consumption) at the high engine speeds; a slightly inferior blow-out limit (250 rpm higher); equally successful starts at altitudes between 5000 and 30,000 feet but somewhat longer acceleration time; and similarly small carbon deposits after $7\frac{1}{2}$ hours of operation. These small differences, however, are attributable to the normal reproducibility of test conditions and the scatter of data for this type of investigation.

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Cross References

Carbon Deposition from AN-F-58 Fuels in a J33 Single Combustor. By Jerrold D. Wear and Edward W. Douglass. NACA RM E9D06, 1949. (See II-B-2.)

Combustion Efficiency Performance of a MIL-F-5624 Type Fuel and Monomethylnaphthalene in a Single Vaporizing-Type Combustor. By Anthony W. Jones and William P. Cook. NACA RM E51K30, 1952. (See II-A-4.)

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3. JP-4 and JFC Fuel

Comparison of Turbojet-Engine Altitude Performance Characteristics and Ignition Limits with MIL-F-5624A Fuel, Grades JP-3 and JP-4. By Willis M. Braithwaite and Paul E. Renas. NACA RM E51L05, 1952. 6 pp.; 2 tables, 5 figs.; Conf.

The altitude performance and ignition limits of an axial-flow turbojet engine were evaluated in an altitude test chamber with MIL-F-5624A, grade JP-3 fuel (that specified for this engine) and a low-volatility grade JP-4 fuel. The investigation was conducted over a range of altitudes from 10,000 to 55,000 feet.

Use of the JP-4 fuel resulted in an increase in specific fuel consumption of 2 to 5 percent over that obtained with the JP-3 fuel. This increased specific fuel consumption resulted from a combination of reduced combustion efficiency and the lower heat of combustion of the JP-4 fuel. Altitude ignition limits were found to be essentially equal for the two fuels over a range of flight Mach number and fuel-supply temperature. Inspection of the combustors after 6 hours operation with JP-4 fuel revealed no noticeable carbon deposition.

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Altitude Performance of Annular Combustor Type Turbojet Engine with JFC-2 Fuel. By James W. Useller, James L. Harp, Jr., and Zelmar Barson. NACA RM E51J26, 1952. 7 pp.; 6 figs.; 1 table; Conf.

An investigation was made comparing the performance of JFC-2 fuel and unleaded clear gasoline in a 3000-pound-thrust turbojet engine. The JFC-2 fuel was a blend of 75 percent diesel type fuel and 25 percent aviation gasoline. The two fuels performed equally well at rated engine speed at altitudes up to 35,000 feet, but combustion efficiency with the 2956
JFC-2 fuel was lower both at reduced engine speeds and at higher altitudes. Turbine-discharge radial temperature profiles for the two fuels were comparable except at an altitude of 45,000 feet, where the JFC-2 fuel gave a flatter profile than gasoline. At the flight Mach number simulated, low-speed combustion blow-out of the engine was not encountered with either fuel at tail-pipe temperatures above 150° F. Several normal low-altitude engine starts showed no apparent difference in the starting characteristics of the two fuels.

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Cross Reference

Carbon Deposition of Several Special Turbojet-Engine Fuels. By Jerrold D. Wear and James W. Useller. NACA RM E51C02, 1951. (See II-B-2.)

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4. Volatility and Distribution

Effect of Fuels and Fuel-Nozzle Characteristics on Performance of an Annular Combustor at Simulated Altitude Conditions. By Richard J. McCafferty. NACA RM E8C02a, 1948. 19 pp.; 27 figs.; Rest.

As part of a program to study the effects of fuel volatility, fuel composition, and fuel-injection-nozzle characteristics on the combustion performance of turbojet-engine combustors, an investigation was made with an annular combustion chamber operating under conditions simulating zero-ram operation of a turbojet engine at various altitudes and engine rotor speeds. The six fuels investigated included hydrocarbons of the paraffinic and aromatic classes having a boiling range from 104° to 664° F. They were isoheptanes, AN-F-28, AN-F-32, Diesel oil, benzéne, and a high boiling aromatic (solvent 4). The fuel-injection nozzles investigated had capacities of 2.0, 3.0, 7.5, 10.5, and 17.5 gallons per hour. Investigations were made wherein the combustor-inlet-air conditions were each altered independently from conditions near the altitude ceilings.

A low-boiling-temperature fuel of either the aromatic or paraffinic classes gave higher altitude operational limits at low engine rotor speeds, whereas a high-boiling-temperature fuel gave higher operational limits at high engine rotor speeds. Combustion efficiencies at various altitudes at constant engine rotor speeds indicated that the low-boiling-temperature fuels of both classes gave higher combustion efficiencies throughout the range of operational altitudes except near the altitude operational limits of these fuels.

The lower-boiling-temperature paraffinic fuels produced lower values of maximum obtainable temperature rise at severe operating conditions than did the higher boiling paraffinic fuels, but for fuel-air ratios below the point where these maximum values occurred the low-boiling-temperature paraffinic fuels gave better combustion efficiencies.

A reduction in fuel-nozzle size resulted in increased combustion efficiency of the two fuels, AN-F-28 and Diesel oil, at low heat-input or temperature-rise values but produced lower temperature-rise limits. Performance was better with the larger nozzles at high temperature-rise ranges. In general, an optimum fuel-pressure differential (best nozzle capacity for a given temperature rise) exists for AN-F-28 or Diesel-oil fuel that provides a wide operating range of temperature rise at relatively good efficiencies for the sets of altitude operating conditions investigated.

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Vapor-Fuel-Distribution Effects on Combustion Performance of a Single Tubular Combustor. By Richard J. McCafferty. NACA RM E50J03, 1950. 9 pp.; 13 figs.; Rest.

An investigation was conducted using a single 4000-pound-thrust turbojet-engine combustor operating with liquid MIL-F-5616 and gaseous propane fuels to study the effects of hydrocarbon fuel distribution and fuel state on combustion performance. The MIL-F-5616 fuel was injected and atomized with the standard engine pressure-atomizing nozzle; data were available from a previous investigation for the same combustor operating with a different fuel nozzle and a similar (AN-F-32) fuel. The gaseous propane was distributed into the primary combustion zone with four fuel-injector designs. Altitude operational limts and attendant combustion efficiencies and effects of combustor inlet-air variables on combustion efficiency were determined.

Vapor-fuel distribution in the primary combustion zone was important because the altitude operational limits and efficiencies could be varied considerably by use of different fuel injectors that provided different fuel-air mixtures. Higher altitude operational limits and higher combustion efficiencies were obtained with vapor fuel than with liquid fuel atomized and distributed with the two designs of pressure-atomizing nozzle.

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<u>Liquid-Fuel-Distribution and Fuel-State Effects on Combustion Performance of a Single Tubular Combustor.</u> By Richard J. McCafferty. NACA RM E51B21, 1951. 10 pp.; 1 table; 14 figs.; Conf.

An investigation was conducted to study the effects of liquid-fuel distribution on combustion performance of a single turbojet-engine combustor operating with liquid MIL-F-5624 fuel. The MIL-F-5624 fuel was injected with simplex and duplex pressure-atomizing nozzles and four solid-stream fuel distributors. Altitude operational limits and attendant combustion efficiencies and the effects of combustor inlet-air variables on combustion efficiency were determined. Gaseous-fuel-distribution data were available from a previous investigation for the same combustor and, hence, the effect of fuel state on performance was obtained by comparison.

Distribution of liquid fuel within the primary combustion zone of the combustor affects altitude operational limits and combustion efficiency, but to a lesser degree than does gaseous-fuel distribution. Gaseous fuel provided higher altitude operational limits and efficiencies than liquid fuel.

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<u>Combustion Efficiency Performance of a MIL-F-5624 Type Fuel and Monomethylnaphthalene in a Single Vaporizing-Type Combustor.</u> By Anthony W. Jones and William P. Cook. NACA RM E51K30, 1952. 8 pp.; 2 tables; 11 figs.; Conf.

An investigation was conducted with a conventional turbojet fuel, MIL-F-5624 (JP-3), and a low-volatility, high-density hydrocarbon, monomethylnaphthalene, in a vaporizing-type combustor to determine (1) the combustion efficiency of both fuels for variations in inlet-air conditions and fuel flow and (2) to what extent fuel prevaporization would minimize the differences in combustion efficiency previously observed between widely dissimilar hydrocarbon fuels in a conventional atomizing combustor.

A single combustor from a developed turbine-propeller engine incorporating fuel-prevaporization principles and designed for kerosene fuel was used as the vaporizing combustor.

With the single vaporizing-type combustor, the volatile MIL-F-5624 type fuel burned over a wider range of operating conditions and gave combustion efficiencies 2 to 16 percent higher than the low-volatility, high-density fuel, monomethylnaphthalene.

Heat-input rate had little effect on the combustion efficiency of each fuel in the vaporizing-type combustor, whereas with the same fuels in a conventional atomizing-type combustor, a decrease in combustion efficiency was obtained with a decrease in heat input, the greater decrease occurring for the less volatile fuel. The trends indicated that the vaporizing combustor tends to eliminate the differences in fuel atomization and thus diminished the effect of fuel properties on combustion efficiency.

The vaporizer design and capacity were inadequate for the monomethylnaphthalene fuel, however, as evidenced by rich blow-out at rather low air-flow rates. The use of monomethylnaphthalene as a fuel resulted in substantial carbon formation on the liner and the outer surface of the vaporizer.

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Cross References

Effects of Fuel-Nozzle Carbon Deposition on Combustion Efficiency of Single Tubular-Type, Reverse-Flow, Turbojet Combustor at Simulated Altitude Conditions. By Ralph T. Dittrich. NACA TN 1618, 1948. (See II-B-2.)

Effect of Fuel Volatility on Altitude Starting Limits of a Turbojet Engine. By H. D. Wilsted and J. C. Armstrong. NACA RM E50G10, 1950. (See II-C.)

Ignition-Energy Requirements in a Single Tubular Combustor. By Hampton H. Foster. NACA RM E51A24, 1951. (See II-C.)

Effect of Fuel Volatility on Performance of Tail-Pipe Burner. By Zelmar Barson and Arthur F. Sargent, Jr. NACA RM E51C14, 1951. (See II-D.)

Effect of Spark Repetition Rate on the Ignition Limits of a Single Tubular Combustor. By Hampton H. Foster. NACA RM E51J18, 1951. (See II-C.)

Preliminary Results of Turbojet-Engine Altitude-Starting Investigation. By H. D. Wilsted and J. C. Armstrong. NACA RM E51H30, 1951. (See II-C.)

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5. High-Density Fuel

Combustion Efficiency and Altitude Operational Limits of Three Liquid Hydrocarbon Fuels Having High Volumetric Energy Content in a J33 Single Combustor. By Edward G. Stricker. NACA RM E50H28, 1950. 10 pp.; 1 table; 8 figs.; Rest.

The combustion efficiency and the altitude operational limits of three liquid hydrocarbon fuels having high volumetric energy content (decalin, tetralin, and monomethylnaphthalene) were compared with an AN-F-58 fuel in a single tubular combustor from a J33 turbojet engine. The investigation covered a range of simulated engine conditions for altitudes from 20,000 to 60,000 feet; 42- to 107-percent normal rated engine speed; and a flight Mach number of 0.6. The independent effects of combustor-inlet-air temperature, pressure, and mass air flow on the combustion efficiency of the four fuels were determined around standard 2956
combustor-inlet conditions.

At the simulated altitude and combustor-inlet-air conditions investigated, the combustion efficiency for the four fuels generally decreased with an increase in volumetric energy content. The highest values of available energy per unit volume of fuel were obtained in this combustor with decalin fuel; although monomethylnaphthalene fuel had the highest volumetric energy content of the fuels tested, its greatly decreased combustion efficiency values resulted in the lowest values of available energy per unit volume.

The altitude operational limits for decalin and tetralin fuels were higher than for AN-F-58 fuel; monomethylnaphthalene fuel gave the lowest altitude operational limit. It was concluded from these and other related investigations that the satisfactory utilization of high-energy-content fuels will require improved fuel-injection techniques and improved combustor design for alleviating the reduced combustion efficiency, the carbon deposition, and the altitude ignition problems.

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Cross Reference

Combustion Efficiency Performance of a MIL-F-5624 Type Fuel and Monomethylnaphthalene in a Single Vaporizing-Type Combustor. By Anthony W. Jones and William P. Cook. NACA RM E51K30, 1952. (See II-A-4.)

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B. Carbon Deposition and Smoking

1. Laboratory Investigations

Smoking Characteristics of Various Fuels as Determined by Open-Cup and Laboratory-Burner Smoke Tests. By Earl R. Ebersole and Henry C. Barnett. NACA WR E-190, 1945. (Supersedes NACA MR's E5F20 and E5I12.) 6 pp.; 1 table; 9 figs.; Unc.

Inasmuch as the smoking tendency of jet-propulsion fuels is of interest, a laboratory program has been conducted to obtain data on the smoking behavior of fuels. The results of open-cup smoke tests of

25 hydrocarbon fuels and of two series of prepared blends are presented. In order to determine the effect of fuel-air ratio as well as hydrocarbon class on the smoking behavior of fuels, 21 hydrocarbons were tested in a laboratory burner at fuel-air ratios ranging from 0.062 to 0.119. The results of these controlled-burning smoke tests are also presented. Correlation with data from full-scale jet-propulsion tests will be necessary to determine the applicability of the results.

The data obtained from an investigation of the smoking characteristics of 25 hydrocarbons indicate that for uncontrolled burning in an open cup:

2956

1. The smoking tendency of a hydrocarbon fuel is more dependent upon the type of hydrocarbon than upon its boiling point or burning rate.

2. The burning rate of hydrocarbons within a given class tended to decrease with increasing boiling point.

3. The smoking tendency of a commercial kerosene was about four times that of the same kerosene from which aromatics had been removed.

Results obtained from controlled-burning smoke tests indicate that:

1. The smoking tendency of hydrocarbon fuels is dependent upon both the class of hydrocarbon and the fuel-air ratio.

2. Within experimental error the smoking tendency of aromatic and dicyclic hydrocarbons is a linear function of the fuel-air ratio.

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Correlation of Laboratory Smoke Test with Carbon Deposition in Turbojet Combustors. By Arthur M. Busch. NACA RM E9K04, 1950. 7 pp.; 3 tables; 5 figs.; Rest.

A correlation of carbon deposition of 19 fuels in a turbojet combustor as a function of the boiling point and of the flame height at the sooting point of the fuels in a simple wick lamp has been developed for a particular combustor operating at a single set of conditions. Two similar investigations with different combustors, operating conditions, and nine different fuels yielded similar correlations on the same graph. The simple wick lamp is suggested to be of possible value in the evaluation of turbojet fuels.

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Combustion of Smoke in Diffusion and Bunsen Flames. By Thomas P. Clark. NACA RM E51E15, 1951. 8 pp.; 3 figs.; Unc.

Varying amounts of smoke, both in the form of concentrated filaments and dilute homogeneous mixtures with the combustible, were burned in diffusion flames of ethylene and in Bunsen flames of ethylene-air mixtures. Stable flames of both types were found capable of burning large amounts of carbon smoke if the smoke was finely divided.

It was found that finely divided smoke passing through the flame zone in the form of a laminar filament could be completely burned at a relative smoke-fuel carbon ratio within the filament as high as 3.5:1. 2956
Conversely, low over-all concentrations of smoke could pass through the reaction zone without burning completely, if the smoke was agglomerated into flecks of soot. The smoke was found to burn in both the inner and the outer cones of the Bunsen flame.

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<u>Influence of External Variables on Smoking of Benzene Flames.</u> By Thomas P. Clark. NACA RM E52G24, 1952. 9 pp.; 8 figs.; Unc.

Premixed benzene-air flames were burned under a variety of conditions to determine the effect of the conditions on the smoking properties of the flames. Variations in initial gas temperature, fuel-flow rate, flame length, secondary-air-flow rate, and burner-tube diameter were studied. Fuel-air ratios were measured both at the appearance of the first evidence of carbon formation in the flame, and at the point where smoke issued from the flame. Of all the variables studied, temperature alone affected the fuel-air ratio at which the first evidence of carbon formation was visible in the flame.

A critical fuel-air-ratio limit of approximately 164 percent of stoichiometric was discovered below which no smoke was formed by the flame regardless of the conditions existing in the gas surrounding the flame. At fuel-air ratios above 164 percent of stoichiometric, the smoking tendencies of the flame became very dependent on the conditions in the gas surrounding the flame. In general, all variations which tended to replace the exhaust gases around the outer cone with air or to increase the diffusion of oxygen into the outer cone enhanced the smoke-burning properties and decreased the smoking tendencies of the flame.

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<u>Variation in Smoking Tendency Among Low Molecular Weight Hydrocarbons.</u> By Rose L. Schalla and Glen E. McDonald. NACA RM E52I22, 1952. 8 pp.; 3 tables; 5 figs.; Unc.

An investigation was made of the variations in smoking tendency among 38 gaseous and liquid pure hydrocarbon compounds when burned as diffusion flames in still air. The maximum rates at which the fuels could be burned smoke-free varied as follows: n-paraffins > isoparaffins > monoolefins > alkynes > aromatics. Cyclic paraffins and olefins as well as diolefins were also studied. Their position over-lapped the trends of several of the series presented.

Variations in smoking tendencies within the given homologous series were rather complex, but a tentative explanation is that the greater the strength of the carbon bonds or skeleton of the hydrocarbon molecule, the greater will be its tendency to form smoke during combustion. From this suggested explanation a possible mechanism based on dehydrogenation and subsequent polymerization of the carbon nuclei was proposed as the initial step involved in the formation of smoke.

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Examination of Smoke and Carbon from Turbojet-Engine Combustors. By Thomas P. Clark. NACA RM E52I26, 1952. 8 pp.; 2 tables; 2 figs.; Unc.

Smoke and carbon from turbojet-engine combustors were studied by the methods of electron microscopy, chemical analysis, and X-ray diffraction. The smoke exhausting from a combustor was found to consist of carbon black, agglomerated into soot. The carbon black had been partially burned in its passage through the flame zone. The smoke resulted from the incomplete combustion of the vaporized fuel; it was not the result of the pyrolysis of fuel droplets.

The soft carbon in the dome of the combustor liner was found to consist of carbon black and soot intermixed with indeterminate complexes such as high-boiling fuel ends and partly polymerized and pyrolyzed heavy hydrocarbons.

The hard carbon on the walls of the combustor liner was found to be largely a petroleum coke. The coke was apparently formed by the liquid phase cracking, pyrolysis, and subsequent coking on the liner wall of fuel from the spray nozzle.

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2. Combustor and Engine Data

Investigation of Carbon Deposition in an I-16 Jet-Propulsion Engine at Static Sea-Level Conditions. By Edmund R. Jonash, Henry C. Barnett, and Edward G. Stricker. NACA RM E6K01, 1947. 4 pp.; 1 table; 5 figs.; Unc.

In order to study the effect of fuel properties on carbon deposition in jet-propulsion-engine combustors, an investigation was conducted with seven fuels - kerosene, Diesel fuel oil, toluene, xylene, 62-octane gasoline, a commercial solvent, and AN-F-32 (JP-1) - in an

I-16 engine at static sea-level conditions and a constant rotor speed. Data are presented comparing the total carbon deposited by each fuel and curves are presented showing the distribution of carbon deposits among the 10 chambers of the unit. Additional data show the reproducibility of results and the effect of a reduction in exhaust-jet-nozzle area on the carbon-forming tendency of kerosene.

With the exception of Diesel fuel oil, carbon deposition increased with increasing aromatic content of the fuel. A Diesel fuel oil, with an aromatic content of 19 percent, produced carbon deposits exceeding 2956
those resulting from the two 100-percent-aromatic fuels (toluene and xylene). No definite relation between carbon deposition and volatility was established in this investigation.

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<u>Effects of Fuel-Nozzle Carbon Deposition on Combustion Efficiency of Single Tubular-Type, Reverse-Flow Turbojet Combustor at Simulated Altitude Conditions.</u> By Ralph T. Dittrich. NACA TN 1618, 1948. 10 pp.; 7 figs.; Unc.

An investigation was conducted in order to study the effects of changes in fuel-nozzle carbon deposition on the combustion efficiency of a single tubular-type, reverse-flow, turbojet combustor. This investigation was conducted because of the need to improve the reproducibility of combustion data for fuel-research purposes. The inlet-air conditions simulated operation of a single tubular-type combustor of a turbojet engine in the range of altitudes from 20,000 to 45,000 feet and the range of engine speeds from 10,000 to 15,000 rpm.

At a given combustor-inlet condition, the temperature rise obtained with a clean fuel nozzle was observed to increase after operation of the combustor at other simulated altitude conditions. This increase in temperature rise varied from 565° F at low heat inputs to 30° F at high heat inputs. Removal of the carbon deposit from the fuel nozzle permitted reproduction of the original temperature rise. Shielding the fuel-nozzle body from the combustion zone prevented the deposition of carbon on the nozzle at the conditions investigated and improved the reproducibility of temperature-rise data.

In order to simulate the deposition of carbon, the design of the original fuel nozzle was modified to include a divergent section at the exit of the fuel orifice. This change in fuel-nozzle design increased the combustion efficiency at each operating condition investigated.

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Carbon Deposition from AN-F-58 Fuels in a J33 Single Combustor. By Jerrold D. Wear and Howard W. Douglass. NACA RM E9D06, 1949. 10 pp.; 2 tables; 10 figs.; Rest.

An investigation was conducted using a single combustor from a 4700-pound-thrust turbojet engine to determine the amount of carbon deposition of AN-F-58 fuels and the effect of carbon formations in the combustor on the altitude operational limits. Three fuel blends conforming to AN-F-58 specification were prepared in order to determine the influence of boiling temperature and of aromatic content on carbon deposition. The carbon-forming tendencies of the three AN-F-58 fuels and of AN-F-32 fuel were compared at simulated altitudes of 20,000 and 35,000 feet, engine speed of 90-percent normal rated, and flight Mach number of 0.

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Carbon deposition increased with increase in aromatic content and with increase in boiling temperature at constant aromatic content for the AN-F-58 fuels. The values of carbon deposition obtained with AN-F-32 fuel were exceeded only by the values obtained with the AN-F-58 fuel nearest the maximum specification limits of boiling temperature and aromatic content. Altitude operational limits of the high-aromatic AN-F-58 fuel occurred at slightly lower altitudes when the liner and dome assembly contained carbon deposits than when it did not. The ignition plug was fouled with carbon after 17 hours of intermittent operation with a fuel approaching the maximum limits of the AN-F-58 specification at a simulated altitude of 20,000 feet and 90-percent normal rated engine speed.

CN-8

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Carbon Deposition of 19 Fuels in an Annular Turbojet Combustor. By Jerrold D. Wear and Edmund R. Jonash. NACA RM E8K22, 1949. 9 pp.; 2 tables; 9 figs.; Rest.

The effects of fuel properties and change in simulated engine operating conditions on carbon deposition were evaluated in an annular turbojet combustor with a diameter of $10\frac{3}{8}$ inches. The fuel properties examined were specific gravity, volumetric average boiling temperature, hydrocarbon type, and hydrogen-carbon weight ratio. The simulated engine operating conditions ranged from sea level and 50-percent rated engine speed to an altitude of 40,000 feet and rated engine speed. The fuels included hydrocarbons of the paraffinic, olefinic, and aromatic types as well as fuel mixtures.

In general, carbon deposition in the annular combustor increased with increase in boiling temperature of fuels of the same hydrocarbon type. Aromatic fuels deposited more carbon than other types of fuel of the same boiling temperature. An empirical correlation of the carbon deposition, the boiling temperature, and the hydrogen-carbon weight ratio of the fuel was obtained.

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Carbon Deposition of Several Special Turbojet-Engine Fuels. By Jerrold D. Wear and James W. Useller. NACA RM E51C02. 1951. 8 pp.; 1 table; 3 figs.; Rest.

Investigations were conducted to determine the carbon-forming characteristics of MIL-F-5624 and MIL-F-5161 type fuels in a single combustor from a J33 turbojet engine and of a MIL-F-5161 fuel in a J35 full-scale engine. Single-combustor simulated engine conditions were 20,000-foot altitude, 90-percent rated engine speed, and zero ram. Full-scale engine operation was at sea-level, zero-ram conditions. 2956

The carbon deposition of MIL-F 5624 and MIL-F-5161 fuels obtained in the single combustor could be estimated from a previously established empirical correlation with volumetric average boiling temperature and hydrogen-carbon ratio. The carbon deposition in the full-scale engine using MIL-F-5161 fuel was greater than the deposition normally obtained with MIL-F-5624 fuels. This trend, also noted in other types of turbojet engine, was concluded to be the result of fuel characteristics rather than combustion-chamber configuration. The results obtained in these investigations, together with other available full-scale-engine operational information, indicate that MIL-F-5161 fuels form more carbon than most MIL-F-5624 fuels, as predicted by the correlation, and may result in marginal operation in several turbojet engines.

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Relations Between Fuel Properties and Combustion Carbon Deposition. By Edmund R. Jonash, Jerrold D. Wear, and Robert R. Hibbard. NACA RM E52B14, 1952. 29 pp.; 3 tables; 16 figs.; Rest.

Methods for predicting the carbon-forming propensity of turbojet-engine fuels from results of simple laboratory tests of the fuels are discussed. The accuracy and reliability of the methods, and the simplicity of the laboratory tests required are considered with a view toward the application of such methods for the control of jet fuel quality. The prediction of carbon deposition from fuel characteristics including aromatic content, hydrogen-carbon ratio, distillation temperatures, gravity, and aniline point, and from several empirical laboratory carbon-deposition tests is illustrated with data from several turbojet-combustor test units and a large number of widely different fuels.

Of the methods considered, the prediction of carbon deposition from a function of hydrogen-carbon ratio and volumetric average boiling temperature (NACA K factor) was one of the most accurate. Results of tests of a large number of fuels in a J33 tubular combustor indicated an average deviation of the carbon-deposition data from the predicted correlation of 16 percent, which was comparable to the deviation of 10 to 20 percent expected with data for any one fuel. Since conventional methods for determining the hydrogen-carbon ratio of a fuel may be more complex than would be desirable for routine fuel quality control, empirical correlation methods for estimating this factor were compared. The prediction of carbon deposition from such estimated values of hydrogen-carbon ratio are subject to greater inaccuracies than are encountered in the prediction from determined values of hydrogen-carbon ratio.

Precision comparable to the NACA K factor method was obtained in the prediction of carbon deposition from smoking tendency of the fuel by a laboratory lamp. This method, although requiring one of the least complex test techniques, was considered to require additional data to establish the reproducibility of the test method among laboratories.

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Based on limited data, previously obtained on full-scale turbojet engines, the numerical limits of the fuel quality control methods were established at an NACA K factor of 310 or smoking tendency of 13.

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<u>Effect of Inlet-Air and Fuel Parameters on Smoking Characteristics of a Single Tubular Turbojet-Engine Combustor.</u> By Helmut F. Butze. NACA RM E52A18, 1952. 11 pp.; 3 tables; 10 figs.; Rest.

CN-8 back

An investigation was conducted to determine the effect of systematic variations in inlet-air and fuel parameters on the smoking characteristics of a single tubular turbojet-engine combustor. For comparison purposes, a series of tests was conducted at static sea-level conditions over a range of engine speeds with a full-scale turbojet engine having combustors similar to the single-tube unit investigated. The concentration of smoke in the combustion gases was determined by means of a filter technique whereby smoke particles were deposited on a special filter paper. The optical density of the deposit as determined by a transmission densitometer served as an indication of the amount of smoke in the exhaust gas.

The most pronounced effect on smoke was observed with increases in inlet-air pressure which produced large increases in smoke concentration. As fuel-air ratios were increased, smoke densities increased, passed through a maximum, and finally decreased. Increases in inlet-air velocity reduced maximum smoke densities. The effect of inlet-air temperature and fuel volatility on smoke densities was small. Increases in fuel-inlet temperature increased smoke formation slightly. In the full-scale engine, smoke density increased with increasing engine speed and with decreasing exhaust-nozzle area.

The results obtained during this investigation suggest that carbon is formed in the primary zone of a turbojet combustor and is subsequently partly burned in passing through the flame zone, the unburned portion emerging as smoke, Thus, those factors that either tend to reduce carbon formation in the primary zone, such as decreases in pressure and in primary zone fuel-air ratios, or tend to bring about increased burning of smoke in the flame zone such as increased flame length and combustion-gas temperature, will reduce the concentration of smoke in the exhaust gases.

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Effect of Fuel Properties on Carbon Deposition in Atomizing and Prevaporizing Turbojet Combustors. By Jerrold D. Wear and William P. Cook. NACA RM E52C24, 1952. 13 pp.; 2 tables; 3 figs.; Rest. 2956

Investigations of the effects of fuel properties on combustion-chamber carbon deposition were conducted in single tubular fuel-atomizing and fuel-prevaporizing combustors. The relations of the NACA K factor, the smoking tendency, and a function of smoking tendency and volumetric average boiling temperature to carbon deposition were studied with several fuels varying in chemical and physical properties. The independent effects of increased sulfur, gum, and olefin content of fuels of similar NACA K factor were also studied.

The NACA K factor and the smoking tendency were approximately equally effective in relating carbon-deposition data from the prevaporizing and the atomizing combustors. A function of smoking tendency and volumetric average boiling temperature best correlated the carbon-deposition data obtained in the prevaporizing combustor. This function was somewhat less satisfactory for the data obtained in the atomizing combustor.

Increase in the sulfur content of a JP-3 fuel (MIL-F-5624A) by addition of disulfide oil or mixed butyl mercaptans slightly increased carbon deposition. A maximum increase of 38 percent with reproducibilities of 18 and 9 percent was observed with an increase in sulfur content from 0.38 to 1.40 percent by addition of disulfide oil. Increasing the gum content of JP-3 fuel to at least five times the maximum allowed by specification MIL-F-5624A was possible before an appreciable increase in carbon deposition was obtained. Increasing the bromine number of a JP-3 fuel from 12 to 54 by the addition of olefins had no effect on carbon deposition. It is concluded that only very large increases in gum or sulfur content of a fuel will cause significant increases in carbon deposition that will not be predicted by the NACA K factor.

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Carbon-Deposition Characteristics of MIL-F-5624A Fuels Containing High-Boiling Aromatic Hydrocarbons. By Edmund R. Jonash, Jerrold D. Wear, and William P. Cook. NACA RM E52G11, 1952. 5 pp.; 2 tables; 4 figs.; Rest.

An investigation was conducted in a single J33 combustor to determine the effect of additions of typical high-boiling single-ring and dicyclic aromatic hydrocarbons on the combustor carbon-deposition characteristics of MIL-F-5624A fuels. Triisopropylbenzene and monomethylnaphthalene were used to increase the high-boiling aromatic contents of grade JP-3 and JP-4 fuels. The quantities of carbon deposited after 4-hour combustor operation were compared with those predicted from carbon-deposition correlations previously developed.

The results showed that additions of the high-boiling aromatic components to JP-3 and JP-4 fuels increased carbon deposition. The effects of these fuel components on carbon deposition were satisfactorily predicted by the NACA K factor (function of hydrogen-carbon ratio and volumetric average boiling temperature of the fuel) and the smoking tendency correlations previously developed.

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<u>Effect of Fuel Additives on Carbon Deposition in a J33 Single Combustor. I - Three Metallic-Organic Additives.</u> By Edmund R. Jonash, Jerrold D. Wear, and William P. Cook. NACA RM E52H21, 1952. 7 pp.; 2 tables; 3 figs.; Rest.

An investigation was conducted in a J33 single combustor to determine the effects of three fuel additives on the carbon-deposition characteristics of MIL-F-5624A fuel, grades JP-3 and JP-4, and an aromatic fuel blend. The additives considered included a commercial fuel-oil additive (containing cobalt and lead compounds), tetraethyl lead, and lead naphthenate. The combustor was operated for 4-hour periods at simulated full-scale operating conditions at 90 percent of normal rated engine speed, zero Mach number, and 20,000-foot altitude.

Small concentrations of all additives reduced carbon deposition significantly. A 0.1-percent concentration of the fuel-oil additive in JP-3 fuel reduced carbon deposition 23 percent. Of the two lead additives tested, lead naphthenate was the more effective; a 0.005-percent concentration of this additive reduced the carbon deposition obtained with a highly aromatic fuel blend 66 percent. For at least two of the additives tested, there appeared to be optimum concentrations; larger concentrations caused significant metallic-compound deposition which was included in the reported deposition. The effectiveness of the lead naphthenate additive varied considerably for two widely different fuels considered, an aromatic fuel blend and a JP-4 fuel.

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Cross References

Factors in Selecting Fuels for Gas-Turbine Powered Aircraft. By Louis C. Gibbons. NACA RM E50I18, 1950. (See II-A-1.)

Combustion Efficiency and Altitude Operational Limits of Three Liquid Hydrocarbon Fuels Having High Volumetric Energy Content in a J33 Single Combustor. By Edward G. Stricker. NACA RM E50H28, 1950. (See II-A-5.) 2956

Effect of Retractable Ignition Plug on Plug Fouling by Carbon Deposits. By Jerrold D. Wear and Theodore E. Locke. NACA RM E50F14, 1950. (See II-C.)

Comparison of Performance of AN-F-58 Fuel and Gasoline in J34-WE-22 Turbojet Engine. By Harry W. Dowman and George G. Younger. NACA RM E8L10a, 1949. (See II-A-2.)

Investigation of Afterburner Performance and Afterburner Fuel System Coking of the Westinghouse XJ34-WE-32 Engine. By Louis E. Wallner and William R. Prince. NACA RM E51H28, 1952. (See II-B-2.)

Correlation of Laboratory Smoke Test with Carbon Deposition in Turbojet Combustors. By Arthur M. Busch. NACA RM E9K04, 1950. (See II-B-1.)

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C. Ignition and Starting

Effect of Retractable Ignition Plug on Plug Fouling by Carbon Deposits. By Jerrold D. Wear and Theodore E. Locke. NACA RM E50F14, 1950. 8 pp.; 8 figs.; Rest.

An investigation was conducted using a single combustor from a 4600-pound-thrust turbojet engine to determine if ignition-plug fouling by carbon deposits could be prevented by retracting the plug from the combustion zone during operation after ignition had taken place. The fuels used were normally conducive to forming carbon. Investigations were also made to determine the effect a retractable ignition plug has on starting, altitude combustion efficiency, altitude operational limits, and temperature distribution at the combustor outlet and to compare these results with results obtained using a standard plug.

The retractable ignition plug (withdrawn from combustion zone) was not fouled with carbon deposits at engine conditions or with fuels that did cause the standard plug (in the combustion zone) to become fouled. Starting, altitude combustion efficiencies, and altitude operational limits determined with the standard plug were unaffected by the retractable plug. Temperature distribution at the combustor outlet obtained with the retractable plug was slightly improved over that obtained with the standard plug.

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Investigation of Ignition Characteristics of AN-F-32 and Two AN-F-58a Fuels in Single Can-Type Turbojet Combustor. By Warren D. Rayle and Howard W. Douglass. NACA RM E50H16a, 1950. 7 pp.; 2 tables; 7 figs.; Rest.

An investigation was conducted to determine the ignition characteristics of three typical turbojet-engine fuels (AN-F-32 and two blends of AN-F-58a) in a single can-type combustor. Data obtained over ranges of simulated engine speed and altitude at two flight speeds and over a range of ambient temperature at sea-level static conditions showed the fuel-flow rates required for ignition as functions of fuel characteristics and operating conditions.

The fuel flow required for ignition in the combustor was found to increase with increasing simulated engine speed, with increasing simulated altitude, and with decreasing sea-level ambient temperature. At high altitudes and low ambient temperatures, the fuel flow required for ignition was found to be much greater than the fuel flow required for engine operation. A direct relation was found between the required fuel flow and the A.S.T.M. 10-percent evaporated temperature of the fuel.

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Effect of Fuel Volatility on Altitude Starting Limits of a Turbojet Engine. By H. D. Wilsted and J. C. Armstrong. NACA RM E50G10, 1950. 13 pp.; 3 tables; 10 figs.; Conf.

The lighter fractions of the AN-F-58 specification jet-engine fuel vaporize at the low pressures associated with high-altitude airplane operation where it is possible that as much as 15 percent of the fuel may be lost by evaporation. Use of fuels having a lower volatility than the AN-F-58 fuel would reduce evaporation losses but might change the altitude starting limits of an engine. The effect of fuel volatility on altitude starting limits of an axial-flow-compressor-type turbojet engine was therefore investigated using 1.1- and 5.4-pound-per-square-inch Reid vapor pressure fuels. The 5.4-pound Reid vapor pressure fuel used was an AN-F-58 specification fuel. The AN-F-58 fuel, at flight Mach numbers from 0.40 to 0.85, allowed consistent windmilling starts at 2000 to 8000 feet higher altitudes than obtained with the 1.1-pound Reid vapor pressure fuel. At a flight Mach number of 0.25, ignition could not be established at any altitude with the 1.1-pound-per-square-inch Reid vapor pressure fuel. The trend of increasing altitude starting limit with increasing fuel volatility appears to be general in that similar trends have been observed in earlier investigations with different fuels and engines.

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Ignition-Energy Requirements in a Single Tubular Combustor. By Hampton H. Foster. NACA RM E51A24, 1951. 9 pp.; 1 table; 11 figs.; Conf.

An investigation was conducted to determine the minimum spark energy required for ignition in a single tubular combustor. Data were obtained at simulated static sea-level engine starting conditions for a wide range of ambient temperatures, and also for a range of altitude inlet-air pressures and air-flow rates. The inlet-air pressure and flow rates limiting ignition are compared with those limiting steady-state burning in the combustor. Three different fuels were used to indicate the effect of fuel volatility on ignition. 2956

A decrease in ambient temperature from 70° to -60° F at sea-level engine-cranking conditions required an increase in spark energy from 0.022 to about 1.5 joules for ignition in the combustor with the least volatile fuel investigated; comparable trends were obtained with more volatile fuels. The altitude ignition limits were extended by increasing the spark energy above that of the conventional system. A spark energy of approximately 10 joules per spark at a sparking rate of 8 per second gave satisfactory ignition at combustor-inlet conditions close to the steady-state burning limits of the combustor at low and intermediate air-flow rates. The ignition-energy requirements at both sea-level and altitude combustor-inlet conditions generally decreased with an increase in fuel volatility.

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Cross Reference

Altitude-Ignition Limit of a Turbojet Engine Using a Condenser-Discharge Ignition System. By John C. Armstrong. NACA RM E51F11, 1951. 4 pp.; 2 figs.; Unc.

An investigation has been conducted in an altitude test chamber at the NACA Lewis laboratory to evaluate the altitude-ignition characteristics of a condenser-discharge ignition system installed on a turbojet engine.

With a fuel having a Reid vapor pressure of 1.1 pounds per square inch, ignition was obtained with 4.8 joules per spark at 6 sparks per second at an altitude of 55,000 feet and a flight Mach number of 0.6.

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Effect of Spark Repetition Rate on the Ignition Limits of a Single Tubular Combustor. By Hampton H. Foster. NACA RM E51J18, 1951. 7 pp.; 1 table; 3 figs.; Conf.

An investigation was conducted to determine the effect of spark repetition rate on the altitude ignition limits of a single tubular (turbojet engine) combustor The minimum combustor pressures at which ignition could be obtained were determined for a wide range of spark repetition rates. Data were obtained for two fuels of different volatility, two spark energy levels, and three air-flow rates in the range of altitude engine-windmilling conditions.

An increase in spark repetition rate from 3 to 140 sparks per second reduced the ignition limiting combustor-inlet air pressure from about 2 to 4 inches of mercury for air-flow rates of 1.87 and 2.80 pounds per second per square foot. For the highest air flow, 3.75 pounds per second per square foot, the ignition limiting pressure was reduced about 4 to 12 inches of mercury. The trend was similar for both the low- and high-volatility fuel and for two levels of ignition energy. Previously observed trends of lower ignition-pressure limits with decreased air-flow rates and increased fuel volatility were observed in this investigation.

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<u>Preliminary Results of Turbojet-Engine Altitude-Starting Investigation.</u> By H. D. Wilsted and J. C. Armstrong. NACA RM E51H30, 1951. 9 pp.; 16 figs.; Conf.

The altitude-ignition and altitude-flame propagation limits of a turbojet engine over a range of simulated flight conditions in an altitude chamber are being investigated at the NACA Lewis laboratory. Preliminary results showed that an energy output at the spark gap of 2.13 joules per spark at a spark-repetition rate of 1 spark per second allowed ignition to 50,000 feet at a flight Mach number of 0.6 with fuel and engine-inlet-air temperature at standard NACA free-stream total temperature. The minimum power required for ignition occurred at low spark-repetition rates (on the order of 1 spark/sec) accompanied by relatively high spark energies.

When the standard engine ignition system was used with 1-pound-per-square-inch Reid vapor-pressure fuel at a simulated flight Mach number of 0.6, a reduction in either fuel or inlet-air temperatures progressively reduced the altitude-ignition limit. A reduction in fuel temperature from 30° to -2° F generally lowered the altitude-ignition limit less than 5000 feet but when the fuel temperature was reduced to -30° F a very abrupt lowering of the altitude limit was found when the air temperature was lower than 0° F. At sea-level conditions, however, ignition with the standard ignition system was obtained to the limit of the refrigerated air systems, -50° F. The effects of spark-gap location and fuel volatility were also investigated.

At a simulated flight Mach number of 0.4, a 1.0-pound-per-square-inch Reid vapor pressure fuel decreased the altitude-ignition limit by 15,000 feet when compared with a 6.2-pound fuel. At higher Mach numbers this difference was less.

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Cross References

Factors in Selecting Fuels for Gas Turbine Powered Aircraft. By Louis C. Gibbons. NACA RM E50I18, 1950. (See II-A-1.)

Comparison of Performance of AN-F-58 Fuel and Gasoline in J34-WE-22 Turbojet Engine. By Harry W. Dowman and George G. Younger. NACA RM E8L10a, 1949. (See II-A-2.)

Altitude-Wind-Tunnel Investigation of AN-F-58 Fuel in Experimental Version of J47 Turbojet Engine. By Carl L. Meyer. NACA RM E8L13, 1949. (See II-A-2.) 2956

Comparison of Turbojet-Engine Altitude Performance Characteristics and Ignition Limits with MIL-F-5624A Fuel, Grades JP-3 and JP-4. By Willis M. Braithwaite and Paul E. Renas. NACA RM E51L05, 1952. (See II A-3.)

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D. Tail-Pipe Burning

Effect of Fuel Volatility on Performance of Tail-Pipe Burner. By Zelmar Barson and Arthur F. Sargent, Jr. NACA RM E51C14, 1951. 6 pp.; 1 table; 11 figs.; Conf.

As part of an investigation to determine the performance possibilities of lower-volatility fuels, two fuels having Reid vapor pressures of 6.3 and 1.0 pounds per square inch, respectively, were investigated in a tail-pipe burner on an axial-flow turbojet engine. A flight Mach number of 0.6 was simulated at altitudes from 20,000 to 45,000 feet. The first fuel was MIL-F-5624 and the other a similar base stock with the lighter fractions removed.

With the burner configuration used in this investigation, having a mixing length of only 8 inches between the fuel manifold and the flame holder, the low-vapor-pressure fuel gave lower combustion efficiency at a given tail-pipe fuel-air ratio. For operation with a fixed exhaust-nozzle area this reduction in burner efficiency resulted in lower temperatures and pressures in the tail-pipe and at the turbine outlet, with an attendant decrease in net thrust and rise in specific fuel consumption. The maximum operational altitude of the tail-pipe burner was practically unaffected by the change in fuel volatility.

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Investigation of Afterburner Performance and Afterburner Fuel System Coking of the Westinghouse XJ34-WE-32 Engine. By Louis E. Wallner and William R. Prince. NACA RM E51H28, 1952. 17 pp.; 11 figs.; Conf.

An investigation of the performance of the Westinghouse XJ34-WE-32 engine with afterburner operative was made in altitude wind tunnel at simulated altitudes from 10,000 to 40,000 feet and flight Mach numbers from 0.52 to 1.05. During the course of the performance work, the fuel-injection holes in the afterburner fuel manifold became plugged because of coke or carbon deposits in the manifold. As a result, a later study was made of this coking problem in an attempt to determine its effect on the afterburner performance.

Changes in altitude and flight Mach number had the normal effects on the afterburning performance parameters; that is, increased pressure in the afterburner raised the combustion efficiency and lowered the specific fuel consumption. Peak combustion efficiencies of 95 and 60 percent were obtained at altitudes of 10,000 and 40,000 feet, respectively. However, reproducible afterburner performance is difficult to obtain because of the coke deposits in the injection holes of the afterburner fuel manifold. Losses in thrust up to 8 percent of the total net thrust of the engine were obtained in a number of instances when some of the fuel-manifold injection holes were plugged with coke deposits. It was found that the formation of coking might be eliminated by the complete purging of the afterburner fuel system with air at the same instant the afterburner was shut off.

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Altitude Wind Tunnel Investigation of High-Temperature Afterburners. By E. William Conrad and Carl E. Campbell. NACA RM E51L07, 1952. 22 pp.; 23 figs.; Conf.

An investigation was conducted in the NACA Lewis altitude wind tunnel to develop an afterburner producing the highest possible exhaust-gas temperatures and having suitable operational characteristics. In order to meet the requirements of military airplanes, maximum effort was concentrated on operation at near-stoichiometric fuel-air ratios. Most of the data were obtained at a nominal burner-inlet pressure of 2450 pounds per square foot; however, additional data were obtained at a nominal pressure level of 925 pounds per square foot.

By the use of adequate flame-holder blockage, long fuel-mixing lengths, and low burner-inlet velocities, and by careful matching of the fuel-injection pattern to the gas-flow pattern, performance approaching theoretical values was obtained with four series of burners having different diffuser inner-cone configurations. For example, at the design burner-inlet pressure level of 2450 pounds per square foot, the maximum exhaust-gas temperature obtained was 3900° R as compared with a theoretical maximum of slightly over 4000° R. Similarly, afterburner combustion efficiencies of at least 95 percent were obtained near maximum operating conditions. Combustion instability was encountered in several configurations; however, these difficulties were overcome by careful attention to flame-holder design and to aerodynamic designs of the diffuser.

Performance was obtained at a pressure level of 2450 pounds per square foot absolute using MIL-F-5572, MIL-F-5616, and MIL-F-5624 fuels. These fuels all gave almost identical performance results. The effects of two ceramic coatings on afterburner shell temperature were also studied. The results of one coating, Uverite, were inconclusive; however, a reduction in shell temperature of about 100° F was obtained with a coating formed by the use of 4-percent ethyl silicate in the afterburner fuel.

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III. RAM-JET ENGINE FUEL

A. Theoretical Performance

Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. I - Octene-1, Aluminum, and Aluminum - Octene-1 Slurries. By Benson E. Gammon. NACA RM E51C12, 1951. 8 pp.; 5 figs.; Conf.

A preliminary analytical evaluation of the air and fuel specific-impulse characteristics of octene-1, aluminum, and aluminum - octene-1 slurries was made.

The adiabatic combustion flame temperature, combustion equilibrium-gas composition, air specific impulse, and fuel-weight specific impulse are presented for each fuel. These data, calculated for a combustor inlet-air temperature of 560° R, are presented for a range of equivalence ratios for octene-1 and for aluminum, and over a range of aluminum - octene-1 ratios at a fixed total fuel-equivalence ratio of 1.0. At an equivalence ratio of 1.0, the adiabatic combustion-gas temperature was 4180° and 6160° R for octene-1 and for aluminum, respectively. At an equivalence ratio of 1.0, the air specific impulse for aluminum was 213.3 ((lb)(sec)/lb air) and 170.4 ((lb)(sec)/lb air) for octene-1. The maximum air specific impulse for octene-1 was 172.8 ((lb)(sec)/lb air) and occurred at an equivalence ratio of 1.2.

At a combustor inlet-air temperature of 560° R, octene-1 gave a better fuel specific impulse on a weight basis than aluminum where both fuels are capable of giving the same air specific impulse.

Aluminum - octene-1 slurries offer a means of increasing the limited air specific impulse values available with octene-1 or hydrocarbon-type fuels.

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Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. II - Magnesium and Magnesium - Octene-1 Slurries. By Benson E. Gammon. NACA RM E51C23, 1951. 7 pp.; 8 figs.; Conf.

A preliminary analytical evaluation of the air and fuel specific-impulse characteristics of magnesium and magnesium - octene-1 slurries was made.

Adiabatic combustion flame temperature, air specific impulse, and fuel-weight specific impulse are given for each fuel. The air- and fuel-weight specific-impulse data for octene-1, which was taken as representative of hydrocarbon performance, are presented for comparison.

The combustion flame temperatures available with magnesium and magnesium - octene-1 slurries are greater than those for octene-1. The air specific impulse, or thrust, available for magnesium and for magnesium - octene-1 slurries exceeds that available for octene-1. Ram-jet combustor operation with magnesium hydrocarbon slurries offers a means of improving the fuel-weight specific impulse attainable with magnesium alone and of increasing the limiting air specific impulse attainable with hydrocarbon alone.

Under the conditions considered in the calculations, aluminum gives a better fuel-weight specific impulse than magnesium for all air-specific-impulse values less than 185; for air-specific-impulse values greater than 185, magnesium apparently gives superior fuel-weight specific-impulse values. Under the conditions considered in the calculations, magnesium - octene-1 slurries are roughly equal, or superior, to aluminum - octene-1 slurries with respect to fuel-weight specific impulse at a fixed air specific impulse.

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<u>Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. III - Diborane, Pentaborane, Boron, and Boron - Octene-1 Slurries.</u> By Benson E. Gammon. NACA RM E51D25, 1951. 8 pp.; 6 figs.; Conf.

An analytical evaluation of the air and fuel specific-impulse characteristics of diborane, pentaborane, boron, and boron - octene-1 slurries has been made.

Adiabatic constant-pressure combustion temperature, air specific impulse, and fuel specific impulse are given for each fuel. The specific-impulse data for octene-1, taken as representative of aviation-gasoline performance, are presented for comparison.

At an initial air temperature of 560° R and a pressure of 2 atmospheres, the adiabatic constant-pressure combustion temperatures for diborane, pentaborane, and boron were 4840°, 4990°, and 5320° R, respectively, for a fuel equivalence ratio of 1.0.

Diborane, pentaborane, boron, and boron - octene-1 slurries permit the attainment of air specific-impulse values beyond the octene-1 limit. At a fixed air specific impulse, the fuel-weight specific impulse of diborane is better than that for pentaborane, and pentaborane is better than boron. Boron gives a greater fuel-weight specific impulse than octene-1 at all air specific-impulse values less than 141 ((lb)(sec)/lb air). For air specific-impulse values between 141 and 172.8 ((lb)(sec)/lb air), octene-1 gives greater fuel-weight specific impulse values than boron; for air specific-impulse values greater than the 172.8 octene-1 limit, boron gives a fuel-weight specific impulse superior to octene-1.

The fuel-volume specific-impulse values of boron and pentaborane
2956 at a fixed value of air specific impulse are better than the values for the reference fuel, octene-1.

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<u>Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. IV - Hydrogen, α-methylnaphthalene, and Carbon.</u> By Benson E. Gammon. NACA RM E51F05, 1951. 8 pp.; 6 figs.; Conf.

An analytical evaluation of the air and fuel specific-impulse characteristics of hydrogen, α-methylnaphthalene, and graphite carbon has been made.

Adiabatic constant-pressure combustion temperature, air specific impulse, and fuel specific impulse are given for each fuel. The specific impulse data for octene-1, taken as representative of aviation gasoline performance, are presented for comparison.

At an initial air temperature of 560° R and a pressure of 2 atmospheres, the adiabatic constant-pressure combustion temperatures for hydrogen, α-methylnaphthalene, and graphite carbon were 4256°, 4188°, and 4173° R, respectively, for a fuel equivalence ratio of 1.0.

At a given air specific impulse, the decreasing order of fuel-weight specific impulse is hydrogen, octene-1, α-methylnaphthalene, and graphite carbon.

At a given air specific impulse, the decreasing order of fuel-volume specific impulse is graphite carbon, α-methylnaphthalene, octene-1, and hydrogen.

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<u>Effect of Fuel Density and Heating Value on Ram-Jet Airplane Range.</u> By Hugh M. Henneberry. NACA RM E51L21, 1952. 36 pp.; 3 tables; 7 figs.; Conf.

An analytical investigation of the effects of fuel density and heating value on the cruising range of a ram-jet airplane was made.

In order to isolate fuel property effects as much as possible, the optimum compromise between weight and efficiency was approximated for the wing, engine, and fuselage. Fuel-property effects are presented for the optimum designs thus obtained. In addition, the effects of several design variables on ram-jet airplane cruising range are presented for an altitude of 70,000 feet and a Mach number of 3.5. The analysis included initial cruise altitudes from 35,332 to 100,000 feet, Mach numbers from 1.5 to 4.0, and fuel densities from 4 to 200 pounds per cubic foot. Results are based on an airplane initial gross weight of 150,000 pounds and a pay-load and controls weight of 10,000 pounds. 2956

The results indicate that with present-day knowledge of chemical fuels, neither very high nor very low fuel densities have an advantage for long-range flight. Aircraft range was most sensitive to changes in fuel density at low altitudes and high Mach numbers and the best initial cruise conditions for maximum range were between altitudes of 50,000 and 70,000 feet and Mach numbers of 3.0 and 4.0. In assessing the relative range potentialities of possible ram-jet fuels, it was concluded that in spite of its high density, aluminum does not yield so long a range as a hydrocarbon fuel. The most promising fuels investigated for long range were the borohydrides and metallic boron. The range potentialities of the borohydrides and metallic boron were very similar; any choice between them must be based on practical considerations such as cost and ease of application. Aluminum-hydrocarbon slurries were inferior to pure hydrocarbon fuels on a range basis and boron-hydrocarbon slurries were superior to pure hydrocarbons, approaching the practical range potential of pure metallic boron (evaluated at 50 percent of solid-metal density). It was concluded that the practical difficulties associated with the use of liquid hydrogen cannot be justified on a range basis, but if tactical considerations predicate flight at extremely high altitudes, liquid hydrogen must be considered as a possible fuel. The analysis predicted a maximum relative range at an initial altitude of 70,000 feet and a Mach number of 3.6 when diborane fuel was used. At this flight condition, diborane exhibited a range advantage of 59 percent over the hydrocarbon fuel and an advantage of 5 percent over pentaborane.

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Cross Reference

<u>A Preliminary Experimental and Analytical Evaluation of Diborane as a Ram-Jet Fuel.</u> By Benson E. Gammon, Russel S. Genco, and Melvin Gerstein. NACA RM E50J04, 1950. (<u>See III-B-2.</u>)

B. Experimental Performance

1. Hydrocarbon Fuels

a. Fuel Type

Combustion Efficiency of Homogeneous Fuel-Air Mixtures in a 5-Inch Ram-Jet-Type Combustor. By Thaine W. Reynolds and Robert D. Ingebo. NACA RM E52I23, 1952. 11 pp.; 9 tables; 13 figs.; Conf.

Combustion-efficiency data have been obtained for a 5-inch-diameter combustor employing a straight V-gutter flame holder and a simple cone flame holder. The data obtained cover a range of inlet static pressures, temperatures, and velocities for four fuels.

The data have been shown to correlate with the inlet flow variables of static pressure P, temperature T, and velocity V by the empirical parameter $P^{0.3}T/V^{0.8}$ and also with fuel variations by means of a fundamental flame-speed relation.

It has also been shown that the data are in agreement with a mechanism based on the concept that the rate of flame propagation through the unburned mixture is a function of the fundamental flame speed.

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Comparison of Two Fuels in Bumblebee 18-Inch Ram Jet Incorporating Rake-Type Flame Holder. By Fred A. Wilcox and Ephraim M. Howard. NACA RM E8F11, 1948. 11 pp.; 1 table; 17 figs.; Conf.

An investigation to determine the performance of a Bumblebee 18-inch ram jet incorporating a rake-type flame holder was conducted using kerosene and propylene oxide as fuels. Experiments were performed in the Cleveland altitude wind tunnel at approximate pressure altitudes from 20,000 to 35,000 feet and at ram-pressure ratios equivalent to supersonic free-stream Mach numbers over the operable range of fuel-air ratios.

Use of propylene oxide improved the stability of combustion, increased the operable range of fuel-air ratios, and allowed ignition at higher values of combustion-chamber-inlet velocities. At a fuel-air ratio of about 0.070, the combustion efficiency was raised from a value of approximately 57 percent to a value of approximately 85 percent when the fuel was changed from kerosene to propylene oxide. The higher fuel-air ratios and combustion efficiencies attainable with propylene oxide, compared with those attainable with kerosene, resulted in generally higher values of gas total-temperature ratio, net thrust, and net-thrust coefficient with no appreciable change in specific fuel consumption.

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Cross References

Free-Jet Performance of 16-Inch Ram-Jet Engine with Several Fuels. By Fred A. Wilcox. NACA RM E50I06, 1950. (See III-B-1-b.) 2956

Altitude-Test-Chamber Investigation of Performance of a 28-Inch Ram-Jet Engine. IV - Effect of Inlet-Air Temperature, Combustion-Chamber-Inlet Mach Number, and Fuel Volatility on Combustion Performance. By Robert W. Kahn, Shigeo Nakaniski, and James L. Harp, Jr. NACA RM E51D11, 1951. (See III-B-1-d.)

b. Blended Fuels

Combustion-Chamber Performance with Four Fuels in Bumblebee 18-Inch Ram Jet Incorporating Various Rake- or Gutter-Type Flame Holders. By Ephraim M. Howard, Fred A. Wilcox, and David T. Dupree. NACA RM E8I01a, 1948. 14 pp.; 1 table; 17 figs.; Conf.

The effects of using various fuels and several rake- or gutter-type flame-holder configurations in a Bumblebee 18-inch ram jet are presented and discussed. Studies were made in the Lewis altitude wind tunnel at pressure altitudes from 10,000 to 35,000 feet and at ram-pressure ratios equivalent to free-stream Mach numbers from 0.49 to 1.46.

Best performance was obtained with a rake-type flame holder, which has alternate rakes connected to the pilot combustion-chamber outlet by gutters. The three rakes that were connected by gutters to the pilot-combustion-chamber outlet appear to have been more effective as flame holders than the other three rakes.

Use of propylene oxide or a blend of 25-percent propylene oxide and 75-percent kerosene rather than kerosene as fuel resulted in increased combustion efficiency and better stability of combustion. When propylene oxide was used, ignition at higher values of combustion-chamber-inlet velocity and a wider range of operable fuel-air ratio were obtained than with kerosene. At a fuel-air ratio of about 0.070, the combustion efficiency was raised from an approximate value of 59 percent to 85 percent when the fuel was changed from kerosene to propylene oxide in the configuration, which included the rake-type flame holder described above.

The combustion efficiency increased as the combustion-chamber-inlet static temperature was raised from a value of 35° to 130° F.

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Free-Jet Performance of 16-Inch Ram-Jet Engine with Several Fuels. By Fred A. Wilcox. NACA RM E50I06, 1950. 9 pp.; 10 figs.; Conf.

Several fuels were used in a 16-inch ram-jet engine during a free-jet investigation of ram-jet performance in the NACA Lewis altitude wind tunnel. The fuels used were: gasoline (AN-F-48b), kerosene (AN-F-32), blend (by volume) of 50-percent gasoline and 50-percent propylene oxide, blend (by volume) of 75-percent kerosene and 25-percent propylene oxide, and isopentane.

Data are presented showing ranges of operation, combustion efficiencies, and weight and volume specific fuel consumptions obtained with the various fuels. Maximum ranges of operation were obtained with the blends of propylene oxide. Under the more difficult operating conditions (low inlet temperatures), fuels having the lowest 50-percent boiling points gave the highest combustion efficiencies. Gasoline gave minimum values of weight specific fuel consumption, whereas kerosene gave minimum values of volume specific fuel consumption.

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c. Injection and Distribution

Investigation of Effects of Several Fuel-Injection Locations on Operational Performance of a 20-Inch Ram Jet. By W. H. Sterbentz, E. Perchonok, and F. A. Wilcox. NACA RM E7L02, 1948. 15 pp.; 16 figs.; Conf.

The results of an investigation conducted in the NACA Cleveland altitude wind tunnel to determine the effects of several methods of fuel injection on the operational performance of a 20-inch ram jet are presented and discussed. Studies were made to pressure altitudes of 35,000 feet and ram-pressure ratios equivalent to supersonic Mach numbers. Four fuel-injection arrangements using the same flame holder were investigated: (1) a fixed amount of fuel injected within the flame holder in a downstream direction and a variable amount of fuel injected near the ram-jet diffuser inlet in an upstream direction; (2) a fixed amount of fuel injected within the flame holder in a downstream direction and a variable amount of fuel injected near the flame holder in an upstream direction; (3) all the fuel injected near the ram-jet diffuser inlet in an upstream direction; and (4) all the fuel injected within the flame holder in a downstream direction. The fuel injected upstream of the flame holder was preheated.

The blow-out limits and the combustion stability of each fuel-injection arrangement were determined. In addition, the effects of fuel-air ratio, combustion-chamber-inlet velocity, combustion-chamber-inlet static pressure, and ambient-air pressure on combustion efficiency are presented and analyzed. Engine performance results obtained for the 20-inch ram jet with a 17-inch-diameter exhaust nozzle and one of the fuel-injection arrangements investigated are also presented.

Changes in the location of the point of fuel injection with respect to the flame holder proved to be very important to the performance of the combustion chamber. Pronounced variation in combustion efficiency 2956 with changes in either combustion-chamber-inlet velocity or over-all fuel-air ratio was noted. The range of fuel-air ratios over which combustion could be maintained was decreased when the engine was operated close to the conditions of ram for which choking occurs at the exhaust nozzle. The full fuel-air ratio range of operation, however, was recovered after the engine was choked.

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<u>Effect of Variation in Fuel Pressure on Combustion Performance of Rectangular Ram Jet.</u> By Wesley E. Messing and Dugald O. Black. NACA RM E8I28, 1948. 8 pp.; 1 table; 6 figs.; Conf.

The results of an investigation conducted on a rectangular ram jet to determine the effect of variation in fuel pressure on the starting characteristics, minimum blow-out limits, combustion efficiencies, gas total-temperature ratio, and net-thrust coefficient are presented and discussed. The ram jet was operated over a range of pressure altitudes from 1500 to 26,300 feet, indicated air speeds from 100 to 200 miles per hour, and fuel-air ratios from 0.017 to 0.120. Three different sets of fuel nozzles were used (21.5, 30.0, and 40.0 gal/hr at a pressure differential of 100 lb/sq in.) in order to obtain a range of fuel pressures for a given fuel flow.

Increasing the degree of fuel atomization and distribution by utilization of small-orifice fuel nozzles that operated at high fuel pressures resulted in higher values of combustion efficiency, gas total-temperature ratio, and net-thrust coefficient at a given fuel-air ratio. A maximum fuel pressure was encountered at a given engine air flow for the highest value of combustion efficiency, whereas a further increase in fuel pressure was detrimental because the fuel particles had sufficient momentum to strike and flow along the combustion-chamber wall instead of uniformly mixing with the engine-air flow. When the fuel pressure was increased, the maximum combustion efficiency occurred at lower values of fuel-air ratio. For the same flight condition, the ram jet could be started at lower values of fuel-air ratio when the small-orifice nozzles operating at high fuel pressures were used.

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Effect of Fuel-Air Distribution on Performance of a 16-Inch Ram-Jet Engine. By A. J. Cervenka and E. E. Dangle. NACA RM E52D08, 1952. 10 pp.; 1 table; 9 figs.; Conf.

The effect of combustion on diffusion in the fuel preparation zone of a 16-inch ram-jet engine was determined. The eddy diffusion coefficients were found to vary from 0.6 square foot per second for no burning in the engine to 1.6 square feet per second with burning.

This information was applied in the design of a combustor to operate at lean fuel-air ratios. Operation to a lean fuel-air ratio limit of 0.007 was accomplished with the use of a cylindrical sleeve which limited fuel-air mixing upstream of the flame holder.

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d. Volatility

Altitude-Test-Chamber Investigation of Performance of a 28-Inch Ram-Jet Engine. IV - Effect of Inlet-Air Temperature, Combustion-Chamber-Inlet Mach Number, and Fuel Volatility on Combustion Performance. By Robert W. Kahn, Shigeo Nakaniski, and James L. Harp, Jr. NACA RM E51D11, 1951. 12 pp.; 13 figs.; Unc.

As part of a direct-connect altitude-test-chamber investigation of the combustion performance of a 28-inch-diameter ram-jet engine conducted at the NACA Lewis laboratory, the effects of the following variables on combustion performance were determined:

1. Inlet-air temperature (150° to 350° F)

2. Combustion-chamber-inlet Mach number and pressure (values associated with 55- and 65-percent exhaust nozzles)

3. Fuel density and volatility (commercial grade normal heptane and high-speed Diesel fuel)

In general, increasing inlet-air temperature extended the operable range of fuel-air ratios and permitted operation at lower combustion-chamber pressures. Increasing the inlet-air temperature also increased the combustion efficiency at conditions of high fuel-air ratio and high combustion-chamber-outlet pressure. Raising the combustion-chamber-inlet Mach number and simultaneously lowering the combustion-chamber pressure by increasing the size of the exhaust-nozzle area resulted in increasing the minimum operational combustion-chamber-outlet pressure, lowering the combustion efficiency, and reducing the lean limit of combustion. The use of high-speed Diesel fuel decreased the combustion efficiency 20 to 30 percent below that obtained with heptane within a comparable range of fuel-air ratios.

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Cross References

Comparison of Two Fuels in Bumblebee 18-Inch Ram Jet Incorporating Rake-Type Flame Holder. By Fred A. Wilcox and Ephraim M. Howard. NACA RM E8F11, 1948. (See III-B-1-a.)

Free-Jet Performance of 16-Inch Ram-Jet Engine with Several Fuels. By Fred A. Wilcox. NACA RM E50I06, 1950. (See III-B-1-b.)

2. High-Energy Fuels 2956

a. Metal Hydride Fuel

A Preliminary Experimental and Analytical Evaluation of Diborane as a Ram-Jet Fuel. By Benson E. Gammon, Russell S. Genco, and Melvin Gerstein. NACA RM E50J04, 1950. 17 pp.; 1 table; 16 figs.; Conf.

A preliminary analytical and experimental evaluation of diborane as a ram-jet fuel has been made because there is a need for a ram-jet fuel that will permit a realization of flight range, thrust, and combustion stability beyond those attainable with petroleum fuels. Diborane, though at present expensive and not readily available, is a fuel that appears to offer some of these needed characteristics.

Air specific thrusts of 80 percent of the ideal values were attained for diborane. The experimental air specific thrusts for diborane were approximately equal to the ideal values for octene-1 for corresponding values of the stoichiometric fraction of fuel. With diborane, smooth stable operation of the combustion unit was maintained over a range of fuel-air ratios from 0.0015 to 0.10 and at combustor-inlet-air velocities up to 500 feet per second in the absence of a flame holder. Stable combustion of hydrocarbon fuels was not attained in a combustor employing the identical configuration as that used for diborane. This stability and range of operation is apparently related to the wide inflammability limits and to the extremely high spatial flame speeds of diborane-air mixtures. Spatial flame speeds for diborane-air mixtures as high as 169.5 feet per second were observed under conditions where normal hexane gave a spatial flame speed of 3.22 feet per second or less.

Flight range calculations for an altitude of 20,000 feet, flight Mach number of 1.665, and ambient temperature of 362° R indicate that liquid diborane is capable of maximum ranges as much as 30 to 50 percent greater than that obtained with aviation gasoline, depending upon the weight of equipment necessary to maintain the diborane as a liquid during flight. If diborane is carried as a gas, it is inferior to aviation gasoline from the viewpoint of the available range.

Results of theoretical calculations for maximum adiabatic combustor flame temperature, combustor-gas composition, exit-gas composition, and net internal air specific thrust are also presented.

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Cross Reference

Status of Combustion Research on High-Energy Fuels for Ram Jets. By Walter T. Olson and Louis C. Gibbons. NACA RM E51D23, 1951. (See III-B-2-c.)

b. Metal-Slurry Fuel

Combustion Performance Evaluation of Magnesium-Hydrocarbon Slurry Blends in a Simulated Tail-Pipe Burner. By Leonard K. Tower and J. Robert Branstetter. NACA RM E51C26, 1951. 21 pp.; 3 tables; 17 figs.; Conf.

An experimental investigation was conducted to determine the combustion properties of several magnesium-hydrocarbon slurry blends and to indicate the feasibility of the application of slurry-type fuels to high-speed aircraft. The magnesium fuel blends were evaluated in a 6-inch diameter simulated tail-pipe burner.

High-concentration magnesium slurries showed large improvements in combustion stability and tail-pipe-burner net thrust. The 30- and 60-percent magnesium slurries burned stably between 0 and 1.4 equivalence ratio, limited by pump capacity rather than combustion. Compared with the clear reference hydrocarbon, MIL-F-5624, 30- and 60-percent magnesium slurries produced 15- and 51-percent increase in net tail-pipe burner thrust, corresponding to 5- and 14-percent increase in air specific impulse, respectively. The 60-percent magnesium slurry exhibited an impulse efficiency of 94 percent, the highest of the fuels studied.

At thrusts high enough to exceed the air specific impulse attainable with the reference fuel (160 seconds), the 60-percent magnesium-hydrocarbon slurry exhibited a lower fuel consumption than the 30-percent magnesium slurry. The minimum fuel consumption was attained with MIL-F-5624 fuel at air specific impulse values below 158 seconds.

Highest heat-transfer rates through the wall of the combustor were experienced with the clear reference hydrocarbons; the heat transfer was reduced with increased magnesium concentration in the hydrocarbon fuel, although the apparent combustor-gas temperatures increased with increased magnesium concentration. This reduction in heat transfer was attributed to formation of a magnesium oxide film on the inner wall of the combustor.

Initial results indicate that fairly stable, nonclogging magnesium slurries can be made and injected in a conventional combustor with only minor alterations to pumps, meters, controls, and sprays. The oxide deposition problem in the combustor did not appear serious for the temperature and thrust range covered in this investigation.

2956

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An Experimental Investigation of the Combustion Properties of a Hydrocarbon Fuel and Several Magnesium and Boron Slurries. By Albert M. Lord. NACA RM E52B01, 1952. 13 pp.; 9 figs.; Conf.

An investigation was conducted to explore the characteristics of metal-hydrocarbon combustion, to determine the effect of fuel-air ratio on the combustion efficiency, and to determine how the metal and hydrocarbon separately contribute to the over-all combustion of several slurries. MIL-F-5624 grade JP-3 fuel and slurries of magnesium and boron in JP-3 fuel were investigated.

The combustion efficiency (ratio of energy released to energy available by complete combustion) of magnesium powders in slurries was unaffected by oxygen depletion as a fuel-air ratio was increased above stoichiometric to an equivalence ratio of 1.6, whereas the combustion efficiency of the hydrocarbon declined rapidly. This indicated that the magnesium burns first and the hydrocarbon reaction yields increasing amounts of incomplete combustion products. This effect did not appear in the boron slurries where the oxygen deficiency in the rich region was reflected in incomplete combustion of both the boron and the hydrocarbon.

The relative changes in the combustion efficiencies of the metal and the hydrocarbon with equivalence ratio in effect changed the ratio of metal to slurry that was utilized in the combustion (effective metal fraction). For the range of the experimental data the effective metal fraction was higher at rich mixtures than at lean mixtures; the effective heating value per pound of air was correspondingly higher in the rich region.

The heat released by combustion per pound of air of all the fuels was increased over the values at equivalence ratio of 1.0 by increasing the fuel-air ratio above stoichiometric.

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Effect of Water Vapor on Combustion of Magnesium-Hydrocarbon Slurry Fuels in Small-Scale Afterburner. By Leonard K. Tower. NACA RM E52H25, 1952. 22 pp.; 3 tables; 15 figs.; Conf.

Both JP-3 fuel and a slurry of 60 percent powdered magnesium in JP-3 fuel were evaluated in a small-scale afterburner in the presence of large quantities of water vapor. From data obtained with the small-scale afterburner, the static sea-level performance was computed for turbojet engines augmented by combined water injection and magnesium-slurry afterburning.

Combustion of 60-percent-magnesium slurry in the small-scale afterburner was stable to the highest water-air ratio investigated, 0.18. The JP-3 fuel would not burn beyond a water-air ratio of 0.08.

The following table reveals that total temperature, combustion efficiency, and air specific impulse were improved when the magnesium slurry rather than JP-3 fuel alone was used in the small-scale afterburner both with and without water vapor:

Fuel	Water-air ratio	Afterburner total temperature[1], °R	Afterburner combustion efficiency[1]	Air specific impulse[1], sec
JP-3	0 .07	3650 2800	0.78 .56	157 150
Slurry	0 .12	4760 3720	0.87 .87	177 182

[1]Afterburner equivalence ratio of 1.0.

These improvements were at the expense of increased liquid consumption.

By means of these total-temperature data, turbojet static sea-level performance with combined water injection and afterburning was computed for two engines. One of the engines was assumed to make ideal use of injected water. In the other engine, the effectiveness of water was assumed to be that experienced in previous experiments. Results for an afterburner equivalence ratio of 1.0 were as follows:

Type of water injection	Afterburner fuel	No water injection		Water injection	
		Augmented thrust ratio	Augmented liquid ratio	Maximum augmented thrust ratio	Augmented liquid ratio
Ideal	JP-3 Slurry	1.47 1.75	4.0 6.9	1.81 2.15	6.8 9.8
Experimental	JP-3 Slurry	1.43 1.67	4.0 6.9	1.58 2.00	7.0 13.6

2956

From these results it may be predicted that afterburning with 60-percent-magnesium slurry in place of JP-3 fuel may shorten the take-off distance of some aircraft 17 to 24 percent.

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Effect of Particle Size and Stabilizing Additives on the Combustion Properties of Magnesium Slurry. By Albert M. Lord and Vernida E. Evans. NACA RM E52K12, 1953. 12 pp.; 11 figs.; Conf.

An experimental investigation was conducted with a $1\frac{7}{8}$-inch-diameter burner to determine the effects of particle size and of stabilizing additives on the combustion performance of magnesium-hydrocarbon slurry fuels. The fuels tested were MIL-F-5624A grades JP-3 and JP-4 and slurries of magnesium in JP-3 fuel.

A slurry composed of $4\frac{1}{2}$-micron magnesium particles had a leaner mixture limit at which a flame could be maintained and a maximum blow-out velocity much higher than a slurry composed of 20-micron particles.

The combustion efficiency of the metal in the $4\frac{1}{2}$-micron slurry was consistently higher than in the 20-micron slurry in spite of its being burned at a much higher burner-inlet velocity.

The slurries stabilized with petrolatum had combustion efficiencies and blow-out velocities comparable to those of the gel-stabilized slurries.

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Cross Reference

<u>Status of Combustion Research on High-Energy Fuels for Ram Jets.</u> By Walter T. Olson and Louis C. Gibbons. NACA RM E51D23, 1951. (See III-B-2-c.)

c. Solid Fuel

<u>Status of Combustion Research on High-Energy Fuels for Ram Jets.</u> By Walter T. Olson and Louis C. Gibbons. NACA RM E51D23, 1951. 39 pp.; 5 tables; 27 figs.; Conf.

To assist the research planning of government and industry, a review of the present status of research and development of high-energy fuels for ram-jet propulsion has been made. An examination of published information indicates that eleven organizations in this country have conducted or are conducting experimental investigations on the use of high-energy fuels in ram jets; eight of these organizations are currently active in the field. The materials included in these experiments are aluminum, boron, boron hydrides, carbon, coal and coal-light metal compositions, liquid hydrogen, and magnesium.

On the basis of heating value, fuel density, air specific impulse, and fuel-weight specific impulse, certain substances offer certain performance advantages over conventional hydrocarbon fuels of the gasoline or kerosene type. These performance advantages accruing to a fuel are very much a function of the application intended and perfect generalizations can hardly be made. If beryllium, its compounds, and the undiscovered possibilities among compounds of light metals and hydrogen are not considered because of economic reasons, then, from thermodynamic considerations, the boron hydrides, hydrogen, boron carbide, and boron offer improved range or pay load for long-range, ram-jet powered vehicles. Magnesium, aluminum, and boron, in that order, offer higher thrusts from any tail-pipe burner or ram-jet engine of fixed air-handling capacity, or, conversely, permit the smallest ram-jet engines for a given thrust minus drag. Because these three fuels also have high bulk densities, they offer improved range or pay load for short-range ram-jet vehicles. Highest values of fuel-volume specific impulse belong to boron or boron carbide, carbon, and aluminum in that order. Where solid fuels are to be burned for rather short duration, the simplicity of combustion of solid blocks or fuel beds appears very attractive. Lack of certain thermodynamic data has made complete evaluation of all fuels difficult or impossible.

Although active work on high-energy fuels in the United States dates from late 1945, experimental work may still be considered in the early research stages. The combustion research has been in burners no larger than 6 inches in diameter. Pressed briquettes of carbon, coal, coal and light metals, aluminum, boron, and magnesium formulated with binders and oxidants have been investigated as solid fuel beds installed in ram-jet combustors. Most of the experience with these beds has been with coal and with magnesium. Although some of the combustion tests of these fuel blocks have looked very promising, burning rates and the structural integrity of the fuel block have so far been inadequate for completing flight tests of research vehicles with these fuels.

Only limited exploratory tests have been achieved with methods of feeding solid fuels to ram-jet-type combustors. Aluminum has been fed and burned as wire and powder, coal as powder and pellets, and magnesium as an oxidant-containing flare. All of these methods appear to require new concepts and invention for adequate storage and handling on an aircraft. Solid products of combustion have caused some difficulty in aluminum combustion.

Slurries or suspensions of aluminum, boron, and magnesium and some mixtures of these metals have been prepared in hydrocarbon fuel and burned in exploratory tests in small ram-jet-type combustors. Of these, magnesium slurries in concentrations up to 60 percent by weight have received the most extensive evaluation. Excellent combustion characteristics were reported. More stable slurries of high metal concentration, and improved reliability in the fuel-feed equipment are among the research needs of this very promising technology.

Boron hydrides have received the very briefest of experimental combustion research. Diborane has been shown to burn easily and rapidly, but with the production of deposits. Pentaborane has not been sufficiently available. These promising fuels, although made of readily available elements, are fabulously expensive because of the elaborate chemistry required for their production.

In conclusion, there are fuels other than hydrocarbons that offer performance improvements for ram jets that can be obtained in no other way. Some of these fuels, although more expensive than hydrocarbons, are economically available. Much cheaper boron and boron-derived fuel is needed, however. Research directed at effective utilization of high-energy fuels is still in a sufficiently early stage that effort should not only continue along most of the present lines of attack, but also along such new lines of attack as appear promising.

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Evaluation of End- and Radial-Burning Solid Fuels in Ram Jets Mounted in a Free Jet at Mach Numbers of 2.0, 2.2, and 2.3. By Walter A. Bartlett, Jr. NACA RM L52I19, 1952. 16 pp.; 13 figs.; Conf.

Two types of solid fuels were evaluated in a $6\frac{1}{2}$-inch-diameter ram-jet engine mounted in a free supersonic jet at Mach numbers of 2.0, 2.2, and 2.3. The fuel charges tested were an end-burning fuel, consisting of a solid cylinder $4\frac{1}{2}$ inches in diameter, and a radial-burning fuel in the form of a hollow cylinder, with an inside diameter of $4\frac{1}{4}$ inches and outside diameter of $6\frac{1}{4}$ inches.

Both types of fuel charges gave essentially equal performance. The maximum values of air specific impulse obtainable at a fuel-air ratio of 0.15 are 140 seconds for the end-burning fuel charge (with suitable flame holder) and 145 seconds for the radial-burning fuel.

The peak values of impulse efficiency and combustion efficiency obtained were 83 and 61 percent, respectively, at a fuel-air ratio of 0.08 for both the radial-burning charges and the end-burning fuel with flame holders.

The need for flame-holder installation in the combustor with the end-burning fuel charges was established. Increases in air specific impulse of 30 seconds and in combustion efficiency of 30 percent were obtained with the flame holder installed over those obtained with the fuel charge alone.

The problem of combustion chamber burn-through was encountered even though the combustor shells were constructed of 0.093-inch Inconel. However, this was not experienced when the air specific impulse was less than 130 seconds.

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Flight Test of a Radial-Burning Solid-Fuel Ram Jet. By Walter A. Bartlett, Jr. and H. Rudolph Dettwyler. NACA RM L52K03, 1952. 8 pp.; 12 figs.; Conf.

A flight investigation of a rocket-launched ram-jet engine incorporating a radial-burning solid fuel was made. During the flight the model accelerated from a Mach number of 1.95 and an altitude of 4,200 feet to a Mach number of 2.73 and an altitude of 14,600 feet in 5.5 seconds. In the boost period the fuel successfully withstood an acceleration of 25g. A maximum acceleration of 8.6g was obtained with the value of air specific impulse equal to 148 seconds. The maximum values of net and gross thrust coefficients were 0.49 and 0.61. An over-all fuel specific impulse of 412 seconds was calculated from the data. Combustion-chamber failure was experienced 9.3 seconds after take-off and prevented the ram jet from reaching a higher Mach number.

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Combustion Properties of Aluminum as Ram-Jet Fuel. By J. Robert Branstetter, Albert M. Lord, and Melvin Gerstein. NACA RM E51B02, 1951. 14 pp.; 9 figs.; Conf.

An experimental investigation was conducted to determine the com- 2956
bustion properties of aluminum as a fuel for use in high-speed aircraft. The aluminum fuel was injected both in powder and wire form into 2-inch-diameter ram-jet-type combustors.

Steady combustion was obtained with the aluminum injected in powder form although the thrust was less than that obtained by burning propane at equivalent conditions. The decreased thrust was partly attributed to reduction of nozzle area and to friction losses resulting from aluminum-oxide deposits.

The aluminum wire could be atomized and burned stably with a combustion efficiency of about 75 percent at a combustion-chamber-inlet velocity of 115 feet per second. The investigation covered a range of fuel-air ratios from 31 to 92 percent of stoichiometric.

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IV. ROCKET ENGINE FUEL

A. Theoretical Performance

Theoretical Performance of Some Rocket Propellants Containing Hydrogen, Nitrogen, and Oxygen. By Riley O. Miller and Paul M. Ordin. NACA RM E8A30, 1948. 15 pp.; 5 tables; 11 figs.; Conf.

Theoretical performance data based on frozen equilibrium and isentropic expansion are presented for ranges of mixtures for a number of propellant combinations at a reaction pressure of 300 pounds per square inch absolute and an expansion ratio of 20.4. The fuels considered are liquid hydrogen, hydrazine, liquid ammonia, hydrazine hydrate, and hydroxylamine; the oxidants are liquid ozone, liquid oxygen, and 100-percent hydrogen peroxide. The theoretical data include nozzle-exit temperature, specific impulse, volume specific impulse, and composition, temperature, and mean molecular weight of the reaction products.

The maximum specific impulse for most of the propellants occurred in the fuel-rich region at a reaction-chamber temperature less than the maximum. Maximum volume specific impulse did or did not occur at the point of maximum specific impulse, depending on the relative density of the fuel and oxidant. On the basis of maximum specific impulse alone, the five fuels assumed the following order for any given oxidant: liquid hydrogen, hydrazine, liquid ammonia, and either hydrazine hydrate or hydroxylamine; and the three oxidants with a given fuel had the following order: liquid ozone, liquid oxygen, and 100-percent hydrogen peroxide. On the basis of maximum volume specific impulse alone, the order of the fuels with a given oxidant was hydrazine, hydroxylamine, hydrazine hydrate, liquid ammonia, and liquid hydrogen. With a given fuel, except for ammonia, the oxidant order was: liquid ozone, 100-percent hydrogen peroxide, and liquid oxygen; with ammonia the order, however, was: 100-percent hydrogen peroxide, liquid ozone, and liquid oxygen.

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Theoretical Performance of Diborane as a Rocket Fuel. By Vearl N. Huff, Clyde S. Calvert, and Virginia C. Erdmann. NACA RM E8I17a, 1949. 10 pp.; 5 tables; 2 figs.; Unc.

Theoretical performance data based on equilibrium isentropic expansion and constant-composition (frozen) isentropic expansion from a combustion-chamber pressure of 20.4 atmospheres (300 lb/sq in. absolute) to an ambient pressure of 1 atmosphere are presented for a range of mixtures for four rocket-propellant combinations of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. The theoretical data include combustion-chamber and nozzle-exit temperatures, specific impulse, and volume specific impulse. Composition and mean molecular weight of the reaction products are given for both the combustion chamber and the nozzle exit.

The maximum specific impulse for all the combinations occurred in the fuel-rich region. On the basis of maximum specific impulse, the four oxidants reacting with diborane assumed the following order: liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. On the basis of calculated maximum volume specific impulse, the order of the four oxidants reacting with diborane was: liquid fluorine oxide, liquid fluorine, 100-percent hydrogen peroxide, and liquid oxygen.

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Effect of Combustion-Chamber Pressure and Nozzle Expansion Ratio on Theoretical Performance of Several Rocket Propellant Systems. By Virginia E. Morrell. NACA RM E50C30, 1950. 8 pp.; 3 tables; 4 figs.; Conf.

A brief series of calculations was made for several rocket propellant systems to determine the separate effects of increasing the combustion-chamber pressure and the nozzle expansion ratio on the specific impulse. The propellant combinations were hydrogen-fluorine, hydrogen-oxygen, ammonia-fluorine, AN-F-58 fuel - white fuming nitric acid (95 percent). The results indicate that an increase in specific impulse obtainable with an increase in combustion-chamber pressure is almost entirely caused by the increased expansion ratio through the nozzle.

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Theoretical Performance of Lithium and Fluorine as a Rocket Propellant. By Sanford Gordon and Vearl N. Huff. NACA RM E51C01, 1951. 10 pp.; 3 tables; 6 figs.; Conf.

Theoretical values of performance parameters for liquid lithium and liquid fluorine as a rocket propellant were calculated with the assumptions both of equilibrium composition and of frozen composition during the expansion process for a wide range of fuel-oxidant ratios, combustion pressures, and expansion ratios. The parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

For a chamber pressure of 300 pounds per square inch absolute and an exit pressure of 1 atmosphere, the maximum equilibrium specific impulse value calculated was 335.5 pound-seconds per pound at a weight percent of fuel in mixture of 31.35.

The effect of ionization on the calculated performance was shown to be negligible by a comparison of values of various parameters calculated both with and without ionized substances as products of combustion.

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<u>Theoretical Performance of Liquid Ammonia, Hydrazine, and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines.</u> I - Mixture of Liquid Ammonia and Hydrazine. By Vearl N. Huff and Sanford Gordon. NACA RM E51L11, 1952. 9 pp.; 5 tables; 6 figs.; Rest.

Theoretical values of performance parameters for a mixture of 36.3 percent liquid ammonia and 63.7 percent hydrazine by weight with liquid oxygen bifluoride were calculated on the assumption of equilibrium composition during the expansion process for a wide range of fuel-oxidant and expansion ratios. The parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

The maximum value of specific impulse was 295.8 pound-seconds per pound for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere. Additional calculations were made to determine the effects on performance of a small amount of water in the hydrazine.

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<u>Theoretical Performance of Liquid Ammonia, Hydrazine, and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines. II - Hydrazine.</u> By Vearl N. Huff and Sanford Gordon. NACA RM E52G09, 1952. 7 pp.; 4 tables; 6 figs; Rest.

Theoretical values of performance parameters for hydrazine with liquid oxygen bifluoride were calculated on the assumption of equilibrium composition during the expansion process for a wide range of fuel-oxidant and expansion ratios. Parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

The maximum value of specific impulse was 298.7 pound-seconds per pound for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere. Additional calculations made to determine the effects of 5 percent of water in the hydrazine showed a decrease in performance of 2 to 5 specific-impulse units over the range of fuel-oxidant and expansion ratios presented.

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Theoretical Performance of Liquid Ammonia, Hydrazine, and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines. III - Liquid Ammonia. By Vearl N. Huff and Sanford Gordon. NACA RM E52H14, 1952. 6 pp.; 2 tables; 7 figs.; Rest. 2956

Theoretical values of performance parameters for liquid ammonia with liquid oxygen bifluoride were calculated on the assumption of equilibrium composition during the expansion process for a wide range of fuel-oxidant and expansion ratios. Parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

The maximum value of specific impulse was 291.6 pound-seconds per pound for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere.

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B. Experimental Performance

Investigation of the Diborane - Hydrogen Peroxide Propellant Combination. By William H. Rowe, Paul M. Ordin, and John M. Diehl. NACA RM E7K07, 1948. 7 pp.; 7 figs.; Conf.

Two runs were made with liquid diborane and hydrogen peroxide in a small-scale experimental rocket engine. After the first run, which was very erratic, several modifications were made to the apparatus and test procedure. In the second run combustion started immediately and continued smoothly for the 12 seconds of operation. The diborane - hydrogen peroxide weight ratio investigated was 0.27 (stoichiometric, 0.136). The maximum experimental specific impulse attained during the run was 211 pound-seconds per pound for a combustion-chamber pressure of 237 pounds per square inch gage. This experimental specific impulse was 81 percent of the theoretical specific impulse for the same mixture ratio and combustion-chamber pressure.

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Preliminary Investigation of Hydrazine as a Rocket Fuel. By Paul M. Ordin, Riley O. Miller, and John M. Diehl. NACA RM E7H21, 1948. 17 pp.; 7 figs.; Conf.

The properties of hydrazine, stability and corrosiveness with a number of construction materials, sensitivity to detonation and temperature, and spontaneous reaction with the oxidants, concentrated hydrogen peroxide, sodium permanganate solution, fuming nitric acid, and tetranitromethane, were experimentally investigated. In addition, the theoretical performance of hydrazine with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid was calculated. A brief review of the manufacture, physical, chemical, and physiological properties of hydrazine is given. The results of this investigation indicated that ten metals and three nonmetallic materials were found to be suitable for use with hydrazine at ambient temperatures. Hydrazine decomposed in a closed stainless-steel bomb at constant elevated temperatures or upon gradual heating to elevated temperatures, did not propagate a detonation wave when contained in a 1/2-by-12-inch stainless-steel tube, and produced a violent spontaneous reaction with concentrated hydrogen peroxide, sodium permanganate solution, fuming nitric acid, and tetranitromethane. Theoretical calculations of the maximum specific impulse indicated values of 277.1, 265.7, 247.5, and 241.6 pound-seconds per pound with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid, respectively, at a reaction-chamber pressure of 300 pounds per square inch and an expansion ratio of 20.4.

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Experimental Investigation of Liquid Diborane - Liquid Oxygen Propellant Combination in 100-Pound-Thrust Rocket Engine. By William H. Rowe, Paul M. Ordin, and John M. Diehl. NACA RM E9C11, 1949. 12 pp.; 1 table; 9 figs.; Conf.

The specific impulse of liquid diborane and liquid oxygen over a range of mixture ratios was determined in a 100-pound-thrust rocket engine operating at a combustion-chamber pressure of 300 pounds per square inch absolute.

A faired curve through the experimental data had approximately the same shape as the theoretical curve with a maximum uncorrected experimental specific impulse of 249 pound-seconds per pound at a ratio of fuel weight to total propellant weight of 0.37. When corrected for heat rejection, this value increased to 274 pound-seconds per pound, which is 92 percent of the theoretical value of 299 pound-seconds per pound based on equilibrium expansion for the fuel and the nozzle used. The maximum experimental volume specific impulse was 182 $\times$ 62.4 pound-seconds per cubic foot and occurred at a ratio of fuel weight to total propellant weight of 0.25; the corrected maximum experimental value was 199×62.4 pound-seconds per cubic foot at the same mixture ratio. These experimental values were based on a characteristic length (ratio of combustion-chamber volume to exhaust-nozzle-throat area) of 325 inches. When the characteristic length was reduced from 325 to 159 inches, a small decrease in performance occurred. No apparent change in specific impulse was observed for the two types of injection used for the experiments.

A limited number of temperature- and shock-sensitivity experiments were made with diborane. No explosions nor detonations were observed. 2956

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<u>Experimental Performance of Chlorine Trifluoride - Hydrazine Propellant Combination in 100-Pound-Thrust Rocket Engine.</u> By Paul M. Ordin and Riley O. Miller. NACA RM E9F01, 1949. 11 pp.; 8 figs.; Conf.

The experimental performance of chlorine trifluoride and hydrazine was measured over a range of propellant mixtures in a 100-pound-thrust rocket engine. The engine was operated at a combustion-chamber pressure of approximately 300 pounds per square inch absolute. Experimental values of specific impulse, volume specific impulse, heat rejection per propellant weight, nozzle thrust coefficient, and characteristic velocity were obtained as functions of percent fuel by weight in the propellant mixture.

The maximum measured specific impulse of 234 pound-seconds per pound occurred at a mixture of 33 percent fuel by weight. When corrected for heat rejection to the engine walls, the maximum specific impulse was 247 pound-seconds per pound, 98 percent of the estimated theoretical value for the fuel and the nozzle used. The measured volume specific impulse reached a maximum of 331×62.4 pound-seconds per cubic foot and when corrected for the heat transfer increased to 349×62.4 pound-seconds per cubic foot, both at a mixture ratio containing 33 percent fuel by weight.

The values of heat rejection attained a maximum of approximately 245 Btu per pound of propellant mixture, which corresponds to an over-all heat-flux density of 1.7 Btu per second per square inch, in the mixture range of 30 to 38 percent fuel by weight. The average nozzle thrust coefficient was 1.34 and the maximum characteristic velocity was 5590 feet per second.

The trends, as indicated by the experimental-performance and the heat-rejection curves, were markedly different from what was predicted by theoretical calculations.

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Investigation of the Liquid Fluorine - Liquid Diborane Propellant Combination in a 100-Pound-Thrust Rocket Engine. By Paul M. Ordin, Howard W. Douglass, and William H. Rowe. NACA RM E51I04, 1951. 15 pp.; 2 tables; 20 figs.; Conf.

Specific impulse, volume specific impulse, characteristic velocity, thrust coefficient, and heat rejection of liquid fluorine and liquid diborane for a range of mixture ratio were determined in a 100-pound-
2956 thrust rocket engine designed for a combustion-chamber pressure of 300 pounds per square inch absolute.

In engines with a characteristic length L* (volume/throat area) of 100 inches, the maximum experimental specific impulse obtained was 280 pound-seconds per pound at 14 weight percent of fuel; the correction for the heat rejection (5.28 Btu/(sec)(sq in.)) and for deviations from the reference combustion-chamber pressure raised this value to 286 pound-seconds per pound. The maximum volume specific impulse was 326×62.4 pound-seconds per cubic foot at 11 weight percent of fuel. The characteristic velocity reached a maximum of 6400 feet per second and the experimental thrust coefficient averaged 1.33.

The theoretical performance was recalculated with revised thermodynamic data, indicating a maximum specific impulse of 311 pound-seconds per pound as compared with the previously reported value of 232.

Considerable difficulty was experienced in developing a suitable injector; it was necessary to employ a protective sheath of helium around the diborane injection hole to prevent injector burnout. The results obtained with the various engines indicated lower performance with the 50 L* than with the 100 L* engines using the same injector and comparable amounts of protective helium. Decreasing the quantity of helium or increasing the L* of the engine resulted in higher performance.

Methods of handling and transporting liquid fluorine in a trailer and techniques in condensing gaseous fluorine from commercial supply cylinders were developed.

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C. Ignition Studies

Starting of Rocket Engine at Conditions of Simulated Altitude Using Crude Monoethylaniline and Other Fuels with Mixed Acid. By Dezso J. Ladanyi, John L. Sloop, Jack C. Humphrey, and Gerald Morrell. NACA RM E50D20, 1950. 16 pp.; 10 tables; 11 figs.; Conf.

Experiments were conducted at sea level and at a pressure altitude of approximately 55,000 feet at various temperatures in order to determine the starting characteristics of a commercial 220-pound-thrust rocket engine using crude monoethylaniline and other fuels with mixed acid. 2956

With crude monoethylaniline and mixed acid, ignition difficulties were encountered at sea level and at a pressure altitude of 55,000 feet at temperatures below about 20° F. With fuels (a) mixed butyl mercaptans, (b) clear water-white turpentine, and (c) α-pinene, with mixed acid, no starting difficulties attributable to the propellants were experienced at sea level and at pressure altitudes of 48,000 to 60,000 feet for temperatures as low as -74° F. The turpentine and α-pinene, however, sometimes left deposits on the injector face. With fuel blends, (a) 70 percent furfuryl alcohol and 30 percent crude monoethylaniline by volume, (b) 70 percent furfuryl alcohol and 30 percent xylene by volume, and (c) 90 percent crude monoethylaniline and 10 percent aviation gasoline by volume, with mixed acid, difficulties were experienced either with appreciable deposits or with starting. With any propellent combination at low temperature, the possibility exists that ice from condensed moisture may obstruct or partly obstruct the propellant injection holes and cause ignition failure.

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Low-Temperature Ignition-Delay Characteristics of Several Rocket Fuels with Mixed Acid in Modified Open-Cup-Type Apparatus. NACA RM E50H16, 1950. 13 pp.; 3 tables; 3 figs.; Conf.

An investigation was conducted to determine possible rocket fuels that ignite spontaneously at low temperatures with mixed acid (nitric plus sulfuric) in a more reliable manner than crude N-ethylaniline (monoethylaniline), a rocket fuel in current use. By means of a bench-scale technique a number of fuels were determined to ignite with mixed acid at subzero temperatures; several of these fuels were investigated over a more extended temperature range.

With mixed acid, the following fuels showed generally shorter and less variable ignition-delay intervals than crude N-ethylaniline (over the temperature range of approximately 80° to -40° F): mixed butyl mercaptans, 70 percent (by volume) furfuryl alcohol plus 30 percent crude N-ethylaniline, 63 percent furfuryl alcohol plus 27 percent crude N-ethylaniline and 10 percent methanol, 70 percent furfuryl alcohol plus 30 percent xylene, 35 percent furfuryl alcohol plus 65 percent crude N-ethylaniline, 90 percent commercial gum turpentine plus 10 percent propylene oxide, pure N-ethylaniline, and commercial gum turpentine. Summaries of self-ignition data for these and other fuels are presented.

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Ignition-Delay Characteristics in Modified Open-Cup Apparatus of Several Fuels with Nitric Acid Oxidants within Temperature Range 70° to -105° F. By Riley O. Miller. NACA RM E51J11, 1951. 18 pp.; 4 tables; 4 figs.; Conf.

Ignition-delay characteristics of approximately 90 fuel-oxidant combinations were determined in a modified open-cup apparatus at -40° F. Combinations considered worthy of further study were investigated at temperatures in the range 70° to -105° F. Freezing temperatures of acids were determined as well as viscosities of several fuels at moderate and low temperatures.

At -40° F, several blends of aromatic amines with triethylamine show promise as ignitor fuels with mixed acid (nitric acid plus sulfuric acid) and red fuming nitric acid, and some of these fuels may be useful also with white fuming nitric acid.

Several blends of aromatic amines in triethylamine were found to be fluid at -105° F and red fuming nitric acid containing approximately 3 percent water and 19 percent nitrogen tetroxide was found to freeze at approximately -87° F. With this acid, 30 percent by volume blends of o-toluidine, aniline, and xylidines, respectively, in triethylamine showed desirable ignition characteristics at -76° F, specified maximum freezing temperature for military aviation fuels. With this red fuming nitric acid supercooled to -105° F, 30 percent by volume o-toluidine in triethylamine showed the most consistent ignitibility.

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Ignition Delay Experiments with Small-Scale Rocket Engine at Simulated Altitude Conditions Using Various Fuels with Nitric Acid Oxidants. By Dezso J. Ladanyi. NACA RM E51J01, 1952. 21 pp.; 8 tables; 16 figs.; Conf.

Ignition delay determinations of several fuels with nitric acid oxidants were made at simulated altitude conditions utilizing a small-scale rocket engine of approximately 50 pounds thrust.

With aniline and red fuming nitric acid at room temperatures, ignition delays obtained at initial ambient pressures corresponding to altitudes to 88,000 feet were not significantly different from values obtained at sea-level pressure.

At or below -10° F, explosions or long ignition delays were experienced with hydrazine hydrate and white fuming nitric acid.

Several fuels and various nitric acid oxidants were tested at about -40° F and sea-level pressure. Anhydrous nitric acid always yielded a shorter delay than white fuming nitric acid when tested with 2956
the same fuel. The combination that ignited most rapidly was a diallylaniline - triethylamine mixture and anhydrous nitric acid, which yielded an average ignition delay of about 14 milliseconds.

With a diallylaniline - triethylamine mixture and white fuming nitric acid, ignitions with average delays ranging from 9 milliseconds at 110° F to 22 milliseconds at -50° F were obtained regardless of the initial ambient pressure that ranged from sea-level pressure to a pressure altitude of 88,000 feet. An explosion occurred after ignition in several cases.

With a diallylaniline - triethylamine mixture and a red fuming nitric acid analyzing 3.5 percent water and 16 percent NO_2 by weight, ignitions with no ensuing explosions were obtained with average delays ranging from 13 milliseconds at 110° F to 55 milliseconds at -95° F regardless of the initial ambient pressure that ranged from sea-level pressure to a pressure altitude of 94,000 feet.

From all the runs, it was determined that ignition delay was unaffected by wide variations in time between propellant entries into the combustion chamber.

It was also determined that, with aniline and red fuming nitric acids with essentially equal water contents, a variation in the NO_2 content of the acid from 29 to 35 percent had no significant effect on ignition delay. With other fuels and nitric acids, a decrease in the NO_2 content from 2.5 to 0.5 percent accompanied by a simultaneous increase in the water content from 0.2 to 1.8 percent increased the ignition delay.

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V. FUNDAMENTAL PERFORMANCE

A. Flame Speed Studies

<u>Effect of Hydrocarbon Type and Chain Length on Uniform Flame Movement in Quiescent Fuel-Air Mixtures.</u> By Thaine W. Reynolds and Earl R. Ebersole. NACA TN 1609, 1948. 5 pp.; 1 table; 8 figs.; Unc.

The results of flame-speed measurements of quiescent fuel-air mixtures in a 2.5-centimeter horizontal glass tube of 16 straight-chain hydrocarbons of the paraffin, olefin, diolefin, and acetylene series and of four cyclic hydrocarbons are presented in graphical form.

The paraffin hydrocarbons all had essentially the same peak flame speed. Increased unsaturation in a molecule of given size resulted in a higher peak flame velocity. This effect was most pronounced in the smaller molecules and dropped off rapidly as the chain length was increased. Peak flame speed decreased as the chain length of the unsaturated compounds was increased.

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<u>Fundamental Flame Velocities of Pure Hydrocarbons. I - Alkanes, Alkenes, Alkynes, Benzene, and Cyclohexane.</u> By Melvin Gerstein, Oscar Levine, and Edgar L. Wong. NACA RM E50G24, 1950. 6 pp.; 1 table; 15 figs.; Unc.

The flame velocities of 37 pure hydrocarbons including normal and branched alkanes, alkenes, and alkynes, as well as benzene and cyclohexane, together with the experimental technique employed are presented.

The normal alkanes have about the same flame velocity from ethane through heptane with methane being about 16 percent lower. Unsaturation increases the flame velocity in the order of alkanes, alkenes, and alkynes. Branching reduces the flame velocity.

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<u>Fundamental Flame Velocities of Pure Hydrocarbons. II - Alkadienes.</u> By Oscar Levine, Edgar L. Wong, and Melvin Gerstein. NACA RM E50H25, 1950. 5 pp.; 1 table; 6 figs.; Unc.

Data are presented for the fundamental flame velocities of 10 pure alkadienes that have isolated, conjugated, or cumulative double-bond systems. On the basis of this limited amount of data and the flame velocities previously reported, it is concluded that unsaturation changes the flame velocity in the order alkanes $<$ alkenes $<$ alkadienes with isolated double bonds $\cong$ alkadienes with conjugated double bonds $<$ alkadienes with cumulative double bonds $\cong$ alkynes. There were no significant differences in the flame velocities of *cis* and *trans* 1,3-pentadiene. The alkadienes, 1,2-pentadiene and 2,3-pentadiene, with different positions of the cumulative double bond in the straight chain, have similar flame velocities. Methyl substitution in a hydrocarbon reduces the flame velocity; the extent of the reduction increases with the degree of unsaturation of the hydrocarbon.

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Flame Velocities of Four Alkylsilanes. By Melvin Gerstein, Edgar L. Wong, and Oscar Levine. NACA RM E51A08, 1951. 9 pp.; 1 table; figs.; Conf. 2956

The rates of flame propagation of four alkylsilanes have been determined by a tube method. The maximum fundamental rate of flame propagation increases in the order: tetramethylsilane < trimethylsilane < diethylsilane < monoethylsilane. A precise fundamental flame velocity could not be obtained for monoethylsilane because of the high rate of propagation. In each case the alkylsilanes have considerably higher flame velocities than the hydrocarbons that would result if the silicon were replaced by carbon; whereas, the physical properties of the alkylsilanes resemble those of the corresponding hydrocarbons. On the basis of a qualitative comparison, it appears that the mechanism of the chemical reaction may be important in determining the rate of flame propagation.

When diethylsilane is blended with *n*-pentane, no marked increase in flame velocity occurs until the concentration of diethylsilane is greater than 20 percent. The flame velocities of the blends are lower than would be predicted from a linear blending relation. At no concentration of total combustible does a mixture of diethylsilane and pentane have a higher flame velocity than diethylsilane at a concentration equal to the concentration of total combustible.

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Effect of Initial Mixture Temperature on Flame Speed of Methane-Air, Propane-Air, and Ethylene-Air Mixtures. By Gordon L. Dugger. NACA Rep. 1061, 1952. (Supersedes NACA TN's 2170 and 2374.) 12 pp.; 3 tables; 10 figs.; Unc.

Flame speeds based on the outer edge of the shadow cast by the laminar Bunsen cone were determined as functions of composition for methane-air mixtures at initial mixture temperatures ranging from -132° to 342° C and for propane-air and ethylene-air mixtures at initial mixture temperatures ranging from -73° to 344° C. The data showed that maximum flame speed increased with temperature at an increasing rate. The percentage change in flame speed with change in initial temperature for the three fuels followed the decreasing order, methane, propane, and ethylene. Empirical equations were determined for maximum flame speed as a function of initial temperature over the temperature range covered for each fuel.

For each fuel it was found that, with a fixed parallel-beam shadowgraph system, the ratio of flame speed based on the outer edge of the shadow cast by the flame cone to flame speed based on the inner edge of the shadow was a constant, independent of temperature or composition. The flame speed of propane-air flames was independent of tube diameter from 10 to 22 millimeters or stream-flow Reynolds number from 1500 to 2100.

The observed effect of temperature on flame speed for each of the fuels was reasonably well predicted by either the thermal theory as presented by Semenov or the square-root law of Tanford and Pease. The importance of active radicals in flame propagation was indicated by a simple linear relation between maximum flame speed and equilibrium radical concentrations for all three fuels. Equally good correlations resulted from using either hydrogen-atom concentration alone or a summation of effective relative concentrations of hydrogen atoms, hydroxyl radicals, and oxygen atoms and from using either flame temperatures based on a sodium D-line measurement for a room-temperature mixture or adiabatic flame temperatures.

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<u>Flame Propagation. IV - Correlation of Maximum Fundamental Flame Velocity with Hydrocarbon Structure.</u> By R. R. Hibbard and B. Pinkel. Jour. Am. Chem. Soc., vol. 73, no. 4, Apr. 1951, pp. 1622-1625.

A correlation has been developed between the maximum fundamental flame velocity of hydrocarbons burning in air and the structure of the hydrocarbon. This maximum velocity appears to be a function of the concentrations of the various types of carbon-hydrogen bonds in the inflammable mixture. Maximum flame velocities can be calculated from an equation of the type: flame velocity = $N_A K_A + N_B K_C + N_C K_C$. . . are the concentrations of the various types of C-H bonds and K_A, K_B, K_C . . . are empirically derived flame speed coefficients. Maximum flame velocities have been calculated for 34 hydrocarbons and compared with experimentally observed values. The average difference between calculated and observed flame velocity is less than 2 percent if one hydrocarbon is omitted from the average and the derived coefficients line up in approximately the order expected from other chemical considerations.

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<u>Fundamental Flame Velocities of Hydrocarbons.</u> By Melvin Gerstein, Oscar Levine, and Edgar L. Wong. Ind. and Eng. Chem., vol. 43, no. 12, Dec. 1951, pp. 2770-2772.

The fundamental flame velocities of 54 pure hydrocarbons are reported as determined by a modified tube method. It is concluded that unsaturation increases fundamental flame velocity in the order alkanes $<$ alkenes $<$ alkadienes with isolated double bonds $\cong$ alkadienes with conjugated double bonds $<$ alkadienes with cumulated double bonds $\cong$ alkynes. 2956
Methyl substitution in a hydrocarbon reduces the flame velocity; the extent of the reduction increases with the degree of unsaturation of the hydrocarbon.

The fundamental flame velocities of 5 cycloalkanes indicate that the presence of a ring leads to increased flame velocities. The cycloalkanes usually have higher flame velocities than their aliphatic isomers for rings containing 3 or 4 carbon atoms.

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<u>Flame Velocities over a Wide Composition Range for Pentane-Air, Ethylene-Air, and Propyne-Air Flames.</u> By Dorothy M. Simon and Edgar L. Wong. NACA RM E51H09, 1951. 14 pp.; 4 tables; 12 figs.; Unc.

The change in flame velocity with fuel concentration in air was investigated in order to determine whether an active particle diffusion mechanism of flame propagation is consistent with the observed velocity changes, and to show whether the simplified diffusion mechanism as expressed by the Tanford and Pease equation is sufficiently exact to predict the velocity change with fuel concentration in air. Spatial flame velocities were measured for nearly the total flammability range for pentane-air, ethylene-air, and propyne-air mixtures by a modified tube method at atmospheric pressure and 25° C. Flame shape as revealed by direct photographs was studied. Flame front areas were measured from the direct photographs for different fuel concentrations in air. Fundamental flame velocities were calculated for the concentration range from 60 to 130 percent stoichiometric for the three hydrocarbons. Equilibrium flame tamperatures and equilibrium free radical concentrations were calculated for pentane, ethylene, and propyne over the total flammability range in air. The velocity measurements together with these calculated concentrations were used for a quantitative evaluation of the active particle diffusion theory. It is shown that a general diffusion mechanism is consistent with the observed changes in flame velocity with fuel concentration, and that a form of the Tanford and Pease equation which includes a flame velocity term independent of diffusion will predict the velocity changes over a limited concentration range.

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B. Ignition and Flammability

Relation Between Inflammables and Ignition Sources in Aircraft Environments. By Wilfred E. Scull. NACA TN 2227, 1950. 55 pp.; 6 tables; 53 figs.; Unc.

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A literature survey was conducted to determine the relation between aircraft ignition sources and inflammables. Available literature applicable to the problem of aircraft fire hazards is analyzed and discussed herein. Data pertaining to the effect of many variables on ignition temperatures, minimum ignition pressures, and minimum spark-ignition energies of inflammables, quenching distances of electrode configurations, and size of openings incapable of flame propagation are presented and discussed. The ignition temperatures and the limits of inflammability of gasoline in air in different test environments, and the minimum ignition pressure and the minimum size of openings for flame propagation of gasoline-air mixtures are included. Inerting of gasoline-air mixtures is discussed.

The results of the survey indicate the necessity for research directed toward the following remedial measures capable of reducing the aircraft-fire hazards:

1. A means of preventing the fuels or fuel vapors from contacting the hot exhaust surfaces

2. A method whereby an extinguishing agent could be released inside and around the exhaust system if a crash were imminent

3. A means of cooling the exhaust duct or gases below the surface-ignition temperatures of gasoline and lubricating oil in the event of a crash

4. A means of increasing the surface-ignition temperatures of gasoline and lubricating oil

5. The possibility of using fuels of reduced volatility

6. A means of eliminating the electrical generating system as an ignition hazard in the event of a crash

7. The inerting of engine nacelles and wing compartments

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Limits of Flammability of Pure Hydrocarbon-Air Mixtures at Reduced Pressures and Room Temperature. By James T. DiPiazza. NACA RM E51C28, 1951. 10 pp.; 1 table; 14 figs.; Unc.

A systematic study was undertaken to determine the effect of molecular structure on the flammability limits of pure hydrocarbon-air mixtures at reduced pressures and room temperature. This report presents results obtained for 17 pure normal paraffins, branched paraffins, and monoolefins.

Limit determinations were made in a closed tube with hot-wire ignition. It was found that the low-pressure limit of propagation of about 34 millimeters of mercury was relatively unaffected by molecular weight, branching, or unsaturation. 2956 The fuel-rich limit of propagation, when expressed as percent stoichiometric fuel, increased markedly with increased molecular weight; whereas, the lean limit of propagation narrowed slightly with molecular weight. Branched paraffins had a slightly decreased range of composition limits when compared to straight-chain isomers. The effect of branching was most evident when two methyl groups were substituted for hydrogen atoms on the same carbon atom. Unsaturation in the form of one double bond (ethylene excepted) had no significant effect when monoolefins were compared to analogous saturated hydrocarbons. Flammability-limit curves were characterized by a two-lobe form. The formation of the fuel-rich lobe was attributed to cool-flame phenomena.

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<u>Pressure Limits of Flame Propagation of Pure Hydrocarbon-Air Mixtures at Reduced Pressures.</u> By Adolph E. Spakowski. NACA RM E52H15, 1952. 9 pp.; 2 tables; 8 figs.; Unc.

The flammability limits of 18 high-boiling hydrocarbons at reduced pressures were studied in a closed flame tube with hot-wire ignition. Characteristic two-lobe flammability-limit curves were exhibited by all the hydrocarbons studied. The minimum pressure limit was not affected by the molecular weight.

The rich limit, the lean limit, and the flammability range, when expressed as volume percent fuel, decreased as the number of carbon atoms increased. However, if the concentration of fuel is expressed as percent stoichiometric, the lean limit of the <u>n</u>-alkanes and <u>n</u>-alkenes attains a maximum value near a molecular weight of 75. Likewise the rich limit of the same two series attains a maximum near a molecular weight of 100. The flammability range, when expressed as volume percent fuel in the mixture, correlated with the molecular weight raised to the -0.70 power. The rich limit correlated with the lean limit raised to the 0.56 power.

A correlation between the lean limit and the net molar heat of combustion held for the <u>n</u>-alkane and <u>n</u>-alkene series through the members containing ten carbon atoms. The heat of combustion of the lean-limit mixtures was substantially a constant.

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Minimum Ignition Energies of Six Pure Hydrocarbon Fuels of the C_2 and C_6 Series. By Allen Metzler, Jr. NACA RM E52F27, 1952. 8 pp.; 3 tables; 9 figs.; Unc.

Minimum spark-ignition energies at reduced pressures are reported 2956 for ethane, ethylene, acetylene, n-hexane, cyclohexane, and benzene; and the mean energy-pressure dependence is established to be $E \propto 1/P^{1.76}$ for four of the fuels investigated. A relation between ignition energy E and maximum flame velocity U_{max} is also presented. This relation includes all the experimental data plus data from other investigators and may be expressed approximately as $U_{max} \propto 1/E^{0.8}$. Such interdependence of the minimum ignition energy and maximum fundamental flame velocity permits a reasonable estimation of either from the other with an accuracy sufficient to discern large differences in various pure fuels.

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Spontaneous Ignition Temperatures of Pure Hydrocarbons and Commercial Fluids. By Joseph L. Jackson. NACA RM E50J10, 1950. 6 pp.; 3 tables; 5 figs.; Unc.

The spontaneous ignition temperatures of 94 pure hydrocarbons and 15 fuels and commercial fluids were determined by a crucible method. The resulting data for the pure compounds are presented as functions of hydrocarbon structure.

An increase in molecular weight results in a decrease in spontaneous ignition temperature for both normal alkanes and normal alkenes; in general, increased branching increases the ignition temperature of alkanes and alkenes. Aromatics have considerably higher spontaneous ignition temperatures than most alkanes or alkenes, with benzene having the highest value for any of the hydrocarbons tested.

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Investigation of Spontaneous Ignition Temperatures of Organic Compounds with Particular Emphasis on Lubricants. By Charles E. Frank, Angus V. Blackham, and Donald E. Swarts. NACA TN 2848, 1952. 22 pp.; 6 tables; 12 figs.; Unc.

The study of spontaneous ignition characteristics of organic compounds has been continued with major emphasis on the various types of lubricating oils. The usefulness of the crucible apparatus previously described in NACA TN 2549 has been extended to these less-volatile materials by employing spray injection as well as dropwise addition of the liquid to the ignition chamber. It has been shown that certain relatively nonvolatile compounds previously considered to have relatively high spontaneous ignition temperatures actually exhibit fundamentally the same ease of ignition as their lower-molecular-weight homologues.

Examination of a variety of lubricants including paraffin oils, 2956
polyethylenes, polyethers, esters of dibasic acids, polypropylenes, and polysisobutylenes has given spontaneous ignition temperatures below approximately 400° C for all except the polyisobutylenes. The unique resistance of the polyisobutylene structure to spontaneous ignition apparently is due to its extremely high percentage of primary hydrogen atoms. Additional data also have been obtained on the influence of additives and metal surfaces on spontaneous ignition temperatures and on the ignition behavior of selected two-component mixtures.

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VI. FUEL SYNTHESIS, PHYSICAL PROPERTIES, ANALYSIS

A. Hydrocarbon Fuel Synthesis

A Convenient Preparation of t-Butylamine. By J. V. Karabinos and K. T. Serijan. Jour. Am. Chem. Soc., vol. 67, no. 10, Oct. 1945, p. 1856.

A convenient method of preparation of relatively large quantities of t-butylamine by catalytic hydrogenation of 2,2-dimethyl-ethyleneimine is described. The imine is prepared by the sulfation of 2-amino-2-methyl-1-propanol, followed by alkali treatment of the 2-amino-2-methyl-1-propanolsulfuric acid. The physical properties of both t-butylamine and 2,2-dimethylethyleneimine are listed.

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The Synthesis and Purification of Aromatic Hydrocarbons. I - Butylbenzene. By Joseph V. Karabinos and Joseph M. Lamberti. NACA TN 1019, 1946. 7 pp.; 1 table; 3 figs.; Unc.

A 13-gallon quantity of butylbenzene was synthesized and purified by large-scale preparation of 4-phenyl-1-butene from benzylmagnesium chloride and allyl chloride with subsequent hydrogenation of the olefin. The physical constants for pure samples of 4-phenyl-1-butene and butylbenzene were determined and the position of the double bond in the olefin was established.

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The Synthesis and Purification of Aromatic Hydrocarbons. II - 1,2,4-Trimethylbenzene. By Earl R. Ebersole. NACA TN 1020, 1946. 9 pp.; 3 figs.; Unc.

A new method for the synthesis and purification of a 14-gallon quantity of 1,2,4-trimethylbenzene is described. This method consists in the chloromethylation of m- and p-xylenes, subsequent formation of ethyl dimethylbenzyl ethers, and hydrogenolysis of the ethers to yield the hydrocarbon. A yield of 35 percent was obtained from a mixture of m- and p-xylenes and a 25-percent yield was obtained from commercial xylenes. Physical properties of the "best" gallon and of the engine sample of 1,2,4-trimethylbenzene are given. Evidence is presented for the existence of two crystalline modifications of 1,2,4-trimethylbenzene.

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The Synthesis and Purification of Aromatic Hydrocarbons. III - Isobutylbenzene, sec-Butylbenzene and tert-Butylbenzene. By C. M. Buess, J. V. Karabinos, P. V. Kunz, and L. C. Gibbons. NACA TN 1021, 1946. 7 pp.; 1 table; 5 figs.; Unc.

The syntheses of isobutylbenzene, sec-butylbenzene, and tert-butylbenzene in 11-gallon quantities are described. The sec-butylbenzene was prepared by reacting sec-butyl alcohol with benzene in the presence of aluminum chloride and anhydrous hydrogen chloride. The tert-butylbenzene was prepared in a similar manner without the use of hydrogen chloride. The preparation of isobutylbenzene involved the reaction of phenylmagnesium bromide with methallyl chloride to yield 2-methyl-3-phenyl-1-propene, which was partly rearranged to 2-methyl-1-phenyl-1-propene. Both olefins were isolated. The physical properties are tabulated and freezing curves are plotted for the five hydrocarbons. 2956

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The Synthesis and Purification of Aromatic Hydrocarbons. IV - 1,2,3-Trimethylbenzene. By J. M. Lamberti, T. W. Reynolds, and H. H. Chanan. NACA TN 1163, 1946. 8 pp.; 1 table; 3 figs.; Unc.

A 6-gallon quantity of 1,2,3-trimethylbenzene was prepared and purified in a four-step synthesis involving the condensation of 1,3-pentadiene with crotonaldehyde. The dimethylcyclohexencarboxaldehydes formed were hydrogenated to give the corresponding isomeric dimethylcyclohexylcarbinols. The dehydration of the carbinols and the subsequent dehydrogenation of the trimethylcyclohexenes yielded the 1,2,3-trimethylbenzene. The over-all yield was 24 percent; the physical properties of the material are given.

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The Synthesis and Purification of Aromatic Hydrocarbons. V - 1-Ethyl-3-Methylbenzene. By Earl R. Ebersole. NACA TN 1164, 1946. 6 pp.; 3 figs.; Unc.

The method used for the synthesis and purification of an 8-gallon quantity of 1-ethyl-3-methylbenzene from m-cresol consists in obtaining m-methylcyclohexanone from m-cresol by hydrogenation followed by oxidation, condensation of the ketone with ethylmagnesium bromide, dehydration of the tertiary alcohol obtained, and dehydrogenation of the olefins to 1-ethyl-methylbenzene. A yield of 28 percent of the theoretical was obtained from 98 percent commercial m-cresol. The physical properties of 1-ethyl-3-methylbenzene are compared with selected values from the literature.

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The Purification and Physical Constants of Aromatic Hydrocarbons. By L. C. Gibbons, J. F. Thompson, et al.: Jour. Am. Chem. Soc., vol. 68, no. 6, June 1946, pp. 1130-1131.

The physical properties, including time-temperature freezing curves, for 11 hydrocarbons are presented herein. The equipment used for determination of the physical properties, and the methods of synthesis and purification of 10-gallon quantities of each hydrocarbon are described.

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Ortho- and Para-Diethylbenzenes. By J. V. Karabinos, K. T. Serijan, and L. C. Gibbons. Jour. Am. Chem. Soc., vol. 68, no. 10, Oct. 1946, pp. 2107-2108.

The physical constants and analyses, including time-temperature freezing curves, for o- and p-diethylbenzenes that had been prepared by condensation of the appropriate ethylphenylmagnesium bromide with diethyl sulfate are given. Both hydrocarbons were also prepared by the Wurtz-Fittig reaction between the appropriate chloroethylbenzenes and ethyl bromide and the yields were compared. The physical constants and oxidation products of the aryl halides prepared in both methods are listed.

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Synthesis of 1,2,3-Trimethylbenzene, 1-Ethyl-3-Methylbenzene, and m-Xylene by Dehydrogenation of Corresponding Cyclohexene Intermediates. By Thaine W. Reynolds, Earl R. Ebersole, et al. Ind. and Eng. Chem., vol. 40, no. 9, Sept. 1948, pp. 1751-1752.

Methods of synthesis for 1-ethyl-3-methylbenzene, 1,2,3-trimethylbenzene, and m-xylene which are applicable to the production of 10-gallon quantities of pure hydrocarbon are described. The three compounds were prepared by the dehydrogenation of suitable cyclohexene intermediates. Physical constants and freezing or melting curves for the three aromatic hydrocarbons are reported.

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o-, m- and p-t Butyltoluenes. By Kasper T. Serijan, Harold F. Hipsher, and Louis C. Gibbons. Jour. Am. Chem. Soc., vol. 71, no. 3, Mar. 1949, pp. 873-875.

The preparation and purification of o- and m-t-butyltoluene by the use of both boron trifluoride and aluminum chloride are described. The o-t-butyltoluene was prepared by the reaction of o-methylphenylmagnesium bromide with t-butyl chloride. The physical properties, including time-temperature freezing or melting curves, and partial infrared spectra of the purified hydrocarbons are tabulated.

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The Synthesis of Methylenecyclobutane, Spiropentane, and 2-Methyl-1-Butene from Pentaerythrityl Tetrabromide. By Vernon A. Slabey. NACA TN 1023, 1946. 7 pp.; 2 tables; 6 figs.; Unc.

Reduction of pentaerythrityl tetrabromide in ethanol with zinc in the presence of sodium carbonate and sodium iodide was found to yield methylenecyclobutane, spiropentane, and 2-methyl-1-butene. Yields were 46 percent methylenecyclobutane, 21 percent spiropentane, and 12 percent 2-methyl-1-butene. The reduction procedure described offers a method of preparing both methylenecyclobutane and spiropentane from the same reaction in yields comparable with individual methods of synthesis previously reported. 2956

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Hydrogenation of Spiropentane. By Vernon A. Slabey. Jour. Am. Chem. Soc., vol. 69, no. 2, Feb. 1947, p. 475.

The hydrogenation of spiropentane and separation of the products, neopentane, 1,1-dimethylcyclopropane and isopentane, are described. The products were identified by their physical constants and an infrared spectroscopic examination. The structures of the products indicate that the strained rings of spiropentane are cleaved by hydrogen preferentially between the methylene groups.

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The Synthesis and Purification of Ethers. By Walter T. Olson, Harold F. Hipsher, et al. Jour. Am. Chem. Soc., vol. 69, no. 10, Oct. 1947, pp. 2451-2454.

The synthesis and purification of 24 ethers of various types are described. Their physical constants and experimental and calculated molar refractions are listed. The purity of the ethers prepared was estimated to be 99.5 mole percent or better. The synthesis, purification and physical constants of t-butyl methallyl ether and p-t-butylanisole are presented for the first time.

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Synthesis of Isopropylcyclopropane. By V. A. Slabey, P. H. Wise, and L. C. Gibbons. Jour. Am. Chem. Soc., vol. 71, no. 4, Apr. 1949, p. 1518.

The method of hydrogenating isopropenylcyclopropane and fractionating the resulting product, isopropylcyclopropane, is described. The physical properties, infrared spectrum, and analyses of the 99.5 mole percent pure product are listed. The physical properties and analyses of the intermediate compound, isopropenylcyclopropane are also given.

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The Physical Properties of Five Isomeric Methyl-t-Butylcyclohexanes. By K. T. Serijan, P. H. Wise, and L. C. Gibbons. Jour. Am. Chem. Soc., vol. 71, no. 6, June 1949, pp. 2265-2266.

The catalytic hydrogenation of o-, m-, and p-t-butyltoluenes and purification and separation of the resulting geometric isomers are described. The physical properties, yields and analyses of the five isomeric methyl-t-butylcyclohexanes are given. The effect of a highly branched group on the formation of the *cis* and *trans* isomers is observed
2956 in the 1,2-disubstituted compound.

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The Reduction of Methyl Cyclopropyl Ketone to Methylcyclopropylcarbinol. By V. H. Slabey and P. H. Wise. Jour. Am. Chem. Soc., vol. 71, no. 9, Sept. 1949, pp. 3252-3253.

Several methods of reducing methyl cyclopropyl ketone to methylcyclopropylcarbinol are described. Sodium and ethanol, lithium aluminum hydride, Raney nickel and copper chromite were all tried. The yield and B.P. of methylcyclopropylcarbinol from each method are stated. The physical constants, analyses and infrared spectrum of the product obtained from the copper chromite reduction at 100^{o} are listed, for this was the superior method.

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Synthesis and Purification of Alkyldiphenylmethane Hydrocarbons. I - 2-Methyldiphenylmethane, 3-Methyldiphenylmethane, 2-Ethyldiphenylmethane, 4-Ethyldiphenylmethane and 4-Isopropyldiphenylmethane. By John H. Lamneck, Jr. and Paul H. Wise. NACA TN 2230, 1950. 10 pp.; 1 table; 5 figs.; Unc.

The syntheses of five alkyldiphenylmethane hydrocarbons, 2-methyldiphenylmethane, 3-methyldiphenylmethane, 2-ethyldiphenylmethane, 4-ethyldiphenylmethane, and 4-isopropyldiphenylmethane are described. The preparation of these hydrocarbons was based on the reaction of the appropriate arylmagnesiumhalides with benzaldehyde to yield the corresponding alkylbenzyhydrols, which were subsequently converted by hydrogenolysis. The physical properties tabulated include melting point, boiling point, index of refraction, density, viscosity, heat of fusion, and heat of combustion. Time-temperature melting curves are plotted for all compounds prepared.

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Synthesis and Purification of Some Alkylbiphenyls and Alkylbicyclohexyls. By Irving A. Goodman and Paul H. Wise. NACA TN 2260, 1951. 19 pp.; 2 tables; 4 figs.; Unc.

The syntheses of nine monoalkylbiphenyls and five of the corresponding bicyclohexyl derivatives containing 13 to 16 carbon atoms are described, including details of the reactions, the isolation and description of intermediate compound where possible, and the methods of purification of the final product. Five of the monoalkylbiphenyls have not been previously reported by other investigators. The separation and the purification of the cis and trans isomers of the bicyclohexyl derivatives are also reported for the first time. Physical properties tabulated are melting point, boiling point, index of refraction, density, viscosity, heat of fusion, and heat of combustion. Distillation curves are plotted for the bicyclohexyl compounds, and time-temperature melting curves are plotted for all compounds that could be crystallized. One of these compounds, 2-butylbiphenyl, had two crystalline modifications melting about 4° C apart.

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Synthesis of Cyclopropane Hydrocarbons from Methylcyclopropyl Ketone. I - 2-Cyclopropylpropene and 2-Cyclopropylpropane. By Vernon H. Slabey and P. H. Wise. NACA TN 2258, 1951. 11 pp.; 1 table; 5 figs.; Unc.

A method by which 2-cyclopropylpropene and 2-cyclopropylpropane can be prepared from methylcyclopropyl ketone is described. The synthesis involves the reaction of methylmagnesium chloride with methylcyclopropyl ketone to yield dimethylcyclopropylcarbinol, the dehydration of the carbinol of 2-cyclopropylpropene, and the hydrogenation of the olefin to 2-cyclopropylpropane. The physical constants and the infrared spectra of the purified hydrocarbons are presented.

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Synthesis of Cyclopropane Hydrocarbons from Methylcyclopropyl Ketone. II - 2-Cyclopropyl-1-Pentene, cis and trans 2-Cyclopropyl-2-Pentene and 2-Cyclopropylpentane. By Vernon A. Slabey and P. H. Wise. NACA TN 2259, 1951. 8 pp.; 1 table; 8 figs.; Unc.

The hydrocarbons - 2-cyclopropyl-1-pentene, cis and trans 2-cyclopropyl-2-pentene, and 2-cyclopropylpentane - were synthesized in high purity and their physical properties and infrared spectra were determined. The olefins were isolated from the dehydration products of methyl-*n*-propylcyclopropylcarbinol, which was prepared by the reaction of *n*-propylmagnesium bromide with methylcyclopropyl ketone. Catalytic hydrogenation of the 2-cyclopropylpentenes yielded 2-cyclopropylpentane. The syntheses of these hydrocarbons are reported herein for the first time.

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Synthesis of Cyclopropane Hydrocarbons from Methylcyclopropyl Ketone. III - 2-Cyclopropyl-1-Butene, cis and trans 2-Cyclopropyl-2-Butene, and 2-Cyclopropylbutane. By Vernon A. Slabey and Paul H. Wise. NACA TN 2398, 1951. 11 pp.; 1 table; 5 figs.; Unc.

The hydrocarbons - 2-cyclopropyl-1-butene, cis and trans 2-cyclopropyl-2-butene, and 2-cyclopropylbutane - were obtained from methylcyclopropyl ketone by reacting the ketone with ethylmagnesium bromide, dehydrating the resultant methylethylcyclopropylcarbinol to a mixture of olefins from which 2-cyclopropyl-1-butene and cis and trans 2-cyclopropyl-2-butene was isolated, and hydrogenating the olefins to 2-cyclopropylbutane. All four hydrocarbons were obtained in high purity for the first time; their physical constants and infrared spectra are presented.

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Synthesis, Purification, and Physical Properties of Hydrocarbons of the Naphthalene Series. I - 1-Methylnaphthalene, 1-Ethylnaphthalene, 1-Butylnaphthalene, and 1-Isobutylnaphthalene. By Harold F. Hipsher and Paul H. Wise. NACA TN 2430, 1951. 12 pp.; 1 table; 3 figs; Unc.

The synthesis, the purification, and several physical properties of four 1-alkylnaphthalenes, 1-methylnaphthalene, 1-ethylnaphthalene, 1-butylnaphthalene, and 1-isobutylnaphthalene, are described. In each case, the hydrocarbon was synthesized from 1-naphthalmagnesium bromide by well-known methods. The final hydrocarbons (a minimum of 2000 ml each) were purified by fractional distillation through 6-foot Podbielniak columns to obtain 500 milliliters of each hydrocarbon with a calculated purity higher than 99 mole percent. The physical properties, determined for material having a calculated purity of 99.8 mole percent or higher, include melting point, boiling points at 760 millimeters of mercury, index of refraction, density at 20° C, kinematic viscosity at four temperatures, heat of fusion, and heat of combustion. Time-temperature melting curves and infrared spectra are presented for the four 1-alkylnaphthalenes.

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Dicyclic Hydrocarbons. I - 2-Alkylbiphenyls. By Irving A. Goodman, and Paul H. Wise. Jour. Am. Chem. Soc., vol. 72, no. 7, July 20, 1950, pp. 3076-3079.

The synthesis and purification of a series of five alkylbiphenyls, substituted in the 2-position by the methyl, ethyl, propyl, isopropyl and butyl radicals, respectively, are described. Each hydrocarbon was estimated to be at least 99 mole percent pure. The physical properties, including heats of fusion and heats of combustion, are listed, along with a description of the equipment used to determine these properties. The 2-butylbiphenyl could be crystallized in either of two modifications.

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Dicyclic Hydrocarbons. II - 2-Alkylbicyclohexyls. By I. A. Goodman and P. H. Wise. Jour. Am. Chem. Soc., vol. 73, no. 2, Feb. 1951, pp. 850-851.

The hydrogenation of 2-methyl, 2-ethyl, 2-propyl, 2-isopropyl and 2-butylbiphenyl to the corresponding bicyclohexyl is described herein. The report includes data on the separation of the pairs of geometrical isomers formed. The usual physical properties, including heats of combustion, are listed, minus the melting points and heats of fusion of the high-boiling isomers — 2-ethyl, 2-propyl, 2-isopropyl, and 2-butylbicyclohexyl, all of which form glasses at low temperatures. 2956

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Dicyclic Hydrocarbons. III - Diphenyl- and Dicyclohexylalkanes through C_{15}. By Kasper T. Serijan and Paul H. Wise. Jour. Am. Chem. Soc., vol. 73, no. 10, Oct. 1951, pp. 4766-4769.

The synthesis and purification of a series of 14 dicyclic alkanes, starting with diphenylmethane and extending through the diphenylpropanes, and the corresponding dicyclohexylalkanes, are described. The physical properties including heats of combustion and viscosities are given. Being listed for the first time are the melting or freezing point values of 8 compounds and the description of 3 new compounds, 2-cyclohexyl-2-(cyclohexane-4-ol)-propane, 2-cyclohexyl-2-(cyclohexene-3-yl)-propane and 2-phenyl-2-cyclohexylpropane.

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Dicyclic Hydrocarbons. IV - Synthesis and Physical Properties of α, α- and α,ω-Diphenyl- and Dicyclohexyl-Pentanes and Hexanes. By Kasper T. Serijan and Paul H. Wise. Jour. Am. Chem. Soc., vol. 73, no. 11, Nov. 1951, pp. 5191-5193.

Data are presented for the synthesis and purification of eight dicyclic hydrocarbons (in a state of 99 mole percent purity or better), consisting of α, α- and α,ω-diphenylpentanes and diphenylhexanes and the corresponding dicyclohexylalkanes. The physical properties, carbon-hydrogen analysis, kinematic viscosity at four temperatures, and heat of combustion are reported.

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Dicyclic Hydrocarbons. V - Synthesis and Physical Properties of the Diphenyl- and Dicyclohexylbutanes. By Kasper T. Serijan and Paul H. Wise. Jour. Am. Chem. Soc., vol. 74, no. 2, Jan. 1952.

The synthesis and properties are described for fourteen hydrocarbons in the diphenyl- and dicyclohexylbutane series. In addition to the usual properties, heats of combustion and viscosities are presented for these compounds which were prepared in a high state of purity. The methods of preparation and properties for dl-2,3-dicyclohexylbutane, meso-2,3-dicyclohexylbutane, 1,3-dicyclohexylbutane, 2,2-diphenylbutane and 2,2-dicyclohexylbutane are reported for the first time.

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B. High-Energy Fuel Synthesis and Preparation

The Preparation, Physical Properties, and Heats of Combustion of Four Alkylsilanes. By Stanley Tannenbaum and Maurice F. Murphy. NACA RM E51A05, 1951. 9 pp.; 2 tables; 1 fig.; Unc.

A group of alkylsilanes consisting of monoethylsilane, diethylsilane, and trimethylsilane were prepared in 65 to 90 percent yield by reduction of the respective alkylchlorosilanes with either lithium hydride or lithium aluminum hydride. Tetramethylsilane was prepared by purification of commercial material. The boiling points, densities, refractive indices, and freezing points were determined and are presented together with a survey of literature values. The heats of combustion, obtained experimentally for the first time, are shown to be in good agreement with calculated values.

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Preparation and Physical Properties of Metal Slurry Fuels. By James B. Gibbs and Preston N. Cook, Jr. NACA RM E52A23, 1952. 13 pp.; 2 tables; 19 figs.; Conf.

A preliminary investigation of the physical properties of slurries and of the use of a metal-soap additive to prepare stable slurries of commercial magnesium, aluminum, and boron powders in a MIL-F-5624 grade JP-3 base fuel has been made. The slurries were prepared and their properties determined in ordinary chemical laboratory apparatus. Data are reported on slurry density, apparent viscosity, apparent surface tension, stability, and fuel-flow characteristics, as affected by slurry composition.

Several of the prepared slurries have physical properties acceptable for combustion-research evaluation and limited flight use; however, further investigations are required to establish the suitability of slurries for extended storage and operational field use.

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C. Physical Properties

Correlation of Physical Properties with Molecular Structure for Some Dicyclic Hydrocarbons having High Thermal-Energy Release per Unit Volume. By P. H. Wise, K. T. Serijan, and I. A. Goodman. NACA Rep. 1003, 1951. (Supersedes NACA TN 2081.) 8 pp.; 3 tables; 5 figs.; Unc.

As part of a program to study the correlation between molecular structure and physical properties of high-density hydrocarbons, the net 2956
heats of combustion, melting points, boiling points, densities, and kinematic viscosities of some hydrocarbons in the 2-n-alkylbiphenyl, 1,1-diphenylalkane, α,ω-diphenylalkane, 1,1-dicyclohexylalkane, and α,ω-dicyclohexylalkane series are presented. Comparisons are made on the following three bases:

1. As members of an homologous series in which the compounds have similar structures and differ in molecular weight

2. As isomers with the same molecular weight and molecular formula but different molecular structure

3. As compounds with the same carbon skeleton but different molecular formulas due to hydrogenation of the aromatic rings

The three series of aromatic hydrocarbons, 2-n-alkylbiphenyl, 1,1-diphenylalkane, and α,ω-diphenylalkane, did not show great differences in heat of combustion per unit volume. These series averaged 20 percent higher than typical aircraft fuels of AN-F-58 specification with respect to this property. The two series of dicyclohexyl hydrocarbons, 1,1-dicyclohexylalkane and α,ω,3-dicyclohexylalkane, had somewhat lower heats of combustion, but still averaged about 13 percent higher than AN-F-58 fuel.

Each series followed its own characteristic pattern in the relation of melting point and structure. The general trend was toward lower melting points by addition of a side chain to the parent hydrocarbon. With two exceptions, the dicyclohexyl compounds melted at lower temperatures than the analogous aromatic hydrocarbons.

The molecular weight had a greater influence on boiling point than the molecular structure. The α,ω-diphenylalkane series, however, showed a more rapid rate of increase in boiling point with increasing molecular weight than the other series of aromatic hydrocarbons.

In these three closely related homologous series of aromatic hydrocarbons, the molecular weight had a greater effect on viscosity than the molecular structure when the substituent groups were all normal alkyl in type. The cyclohexyl derivatives had viscosities 40 to 200 percent higher than the analogous aromatic hydrocarbons.

* * *

Correlation of Physical Properties with Molecular Structure for Some Dicyclic Hydrocarbons Having High Thermal-Energy Release Per Unit Volume - 2-Alkylbiphenyl and the Two Isomeric 2-Alkylbicyclohexyl Series. By Irving A. Goodman and Paul H. Wise. NACA Rep. 1065, 1952. (Supersedes NACA TN 2419.) 10 pp.; 2 tables; 6 figs.; Unc.

Three homologous series of related dicyclic hydrocarbons are presented for comparison on the basis of their physical properties, which include net heat of combustion, density, melting point, boiling point, and kinematic viscosity. The three series investigated include the 2-n-alkylbiphenyl, 2-n-alkylbicyclohexyl (high boiling), and 2-n-alkylbicyclohexyl (low boiling) series through C_{16}, in addition to three branched-chain (isopropyl, sec-butyl, and isobutyl) 2-alkylbiphenyls and their corresponding 2-alkylbicyclohexyls. The physical properties of the low-boiling and high-boiling isomers of the 2-sec-butylbicyclohexyl and 2-iso-butylbicyclohexyl are reported herein for the first time.

Comparisons are made on the following bases:

1. As members of an homologous series in which the compounds have similar structure and differ in molecular weight

2. As isomers with the same molecular weight and molecular formula but different molecular structure due to branching of the side chain or to geometric isomerism

3. As compounds with the same carbon skeleton but different molecular formula due to hydrogenation of the aromatic rings

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Suitability of 18 Aromatic Amines for Overwater Storage when Blended with Aviation Gasoline. By Irving A. Goodman and Howard J. Nelson. NACA WR E-166, 1945. (Supersedes NACA MR E5F20a.) 5 pp.; 2 tables; Unc.

As part of the general investigation of aromatic amines as antiknock additives for aviation fuels, requested by the Air Technical Service Command, Army Air Forces, the NACA Cleveland laboratory has been conducting a program to determine the suitability for overwater storage of fuel blends containing aromatic amines. The tests reported herein were completed in January 1945.

The overwater system for storing aviation fuel blends that contain additives such as amines results in loss of some of the additive to the water layer. An indication of the extent to which this loss can occur is conveniently expressed by the gasoline-water distribution coefficient, which is the ratio of additive concentration in the gasoline to that in the water layer at equilibrium. The significance of this coefficient and the method of experimentally determining it are given in detail in NACA WR E-163. Briefly, the coefficient is calculated from the following equation: 2956

$$K_{wt} = \frac{W_r(W_w + W_e)}{W_e(W_g + W_r)}$$

where

K_{wt} gasoline-water distribution coefficient (weight basis)

W_r weight of amine remaining in gasoline phase at equilibrium

W_e weight of amine extracted by water phase at equilibrium

W_w weight of water

W_g weight of gasoline

The distribution coefficient calculated on a weight basis (concentrations expressed as grams of solute per gram of solution) may be converted to a volume basis (concentrations expressed as grams of solute per milliliter of solution) merely by multiplying by the specific gravity of the gasoline solution. It should be noted that this computed volume coefficient still pertains to the original weight concentration of amine in the fuel. The greater the distribution coefficient, the less will be the quantity of additive extracted by the water and, therefore, the more suitable the additive would be for overwater storage. Relations utilizing the distribution coefficient have been used for estimating the concentration of amine remaining in the gasoline as a function of the gasoline-water ratio by volume in an overwater-storage system.

The overwater-storage suitability of 18 aromatic amines is discussed herein, and a substantiation of some of the postulates proposed in reference 1 concerning the correlation of gasoline-water distribution coefficients with molecular structure is included.

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The Low-Temperature Solubility of 42 Aromatic Amines in Aviation Gasoline. By Richard L. Kelly. NACA WR E-167, 1945. (Supersedes NACA MR E5K09.) 7 pp.; 2 tables; 4 figs.; Unc.

2956

At the request of the Air Technical Service Command, Army Air Forces, a general investigation of the suitability of aromatic amines as antiknock additives for aviation gasoline has been conducted at the NACA Cleveland laboratory between April 1943 and April 1945. The program included the determinations of antiknock effectiveness, of suitability for overwater storage, and of solubility in gasoline at low temperatures for aviation gasolines containing aromatic amines.

The present paper is the third and final report on the solubilities of amines in aviation gasoline at low temperatures, such as would be encountered in cold-weather operation or in flight, and summarizes the data reported in the first two papers (refs. 8 and 9); solubilities of seven additional amines, N-methyl-o-toluidine, N-methyltoluidines from chlorotoluenes, o-ethylaniline, N-methyl-p-ethylaniline, N-methylethylaniline (mixed isomers from chloroethylbenzenes), N-methyl-p-isopropylaniline, and N-methyldiphenylamine, are included herein. Solubilities of the 42 amines were measured at temperatures as low as -65° C, 5° C below the usual Army-Navy freezing specification of -60° C, and at concentrations as high as 10 percent by weight, well above the 1- to 3-percent range in which amines have been used in gasoline. Determination of solubility at -60° C was a particular objective in obtaining the data. Because gasoline composition affects the solubility of the amines, solubilities were determined in an aromatic-free gasoline, a gasoline of known aromatic content, and a typical AN-F-28 fuel.

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Solubility of Water in Hydrocarbons. By R. R. Hibbard and R. L. Schalla. NACA RM E52D24, 1952. 10 pp.; 3 tables; 4 figs.; Unc.

A study of the literature data on the solubility of water in hydrocarbons has shown that (a) the log of the solubility is inversely proportional to the reciprocal of the absolute temperature, (b) there is an apparent critical solution temperature at about 352° C indicated both by extrapolation of the literature data and by Henry's law, and (c) the solubility increases with decreasing hydrogen-to-carbon ratio H/C. The following equation is proposed for the prediction of the solubility of water at any temperature in nonolefinic hydrocarbons and petroleum fractions:

$$\log x = -(4200\ H/C + 1050)(1/T - 0.0016) + 2.00$$

where

x solubility of water in hydrocarbon, mole percent

H/C hydrogen-to-carbon weight ratio for hydrocarbon

T absolute temperature, $^{\circ}K$

This equation has been applied to a few petroleum fractions ranging from gasoline to lubricating oil, and a comparison of the calculated and experimentally determined solubilities shows an agreement which is believed to be adequate for most engineering purposes.

* * *

D. Fuel Analysis

<u>A Method for the Determination of Aromatics in Hydrocarbon Mixtures.</u> By Harold F. Hipsher. NACA WR E-111, 1945. (Supersedes NACA RB E5K06.) 6 pp.; 3 tables; 3 figs.; Conf.

A method has been developed for the estimation of aromatic hydrocarbons in hydrocarbon mixtures. Aromaticity of the mixture is estimated from the change in refractive index that results from the removal of the aromatic portion by a sulfuric acid extraction and subsequent percolation through silica gel. The method is simple and requires approximately 2.5 hours. No attempt is made to identify the individual aromatics.

The method was tested with nine base stocks containing aromatics in concentrations from 0 to 35 percent by volume. A mean deviation of ±0.17 percent was obtained with a maximum error of -0.5 percent. The accuracy of the determination is impaired by the presence of olefins, but the resulting error is insignificant for most aviation fuels in which the olefin content is small. Aromatic amines also interfere and are removed before the determinations are made.

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<u>Ultraviolet Absorption Spectra of Aromatic Amines in Isooctane and in Water.</u> By Adelbert O. Tischler and J. Nelson Howard. NACA WR E-68, 1945. (Supersedes NACA ARR E5H27a.) 11 pp.; 4 tables; 19 figs.; Unc.

A study of the ultraviolet absorption spectra in the 3200 A to 2500 A region of 27 aromatic amines in isooctane and in water solutions is presented. A brief discussion of the relation between the molecular structure of the amines and their absorption spectra is included.

Certain factors that affect the absorption spectra of aromatic amines were experimentally investigated. The spectra were found to be different for the two different solvents. In aqueous aromatic amine solutions the pH was found to be an important factor; the addition of acid to a neutral water solution shifted the absorption spectrum of the amine toward the spectrum of the basic aromatic structure of the amine. Irradiation of aromatic amine solutions with ultraviolet light caused changes in the absorption spectra; water solutions of the amines were more rapidly affected than isooctane solutions.

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Quantitative Analysis for Aromatic Amines in Aviation Fuels by Ultraviolet Spectrophotometry. By Adelbert O. Tischler. NACA WR E-69, 1945. (Supersedes NACA ARR E5H27.) 16 pp.; 6 tables; Unc.

A method of quantitative analysis for individual aromatic amines or mixtures of aromatic amines in hydrocarbon fuel blends by spectrophotometric measurement of ultraviolet-light absorption is presented. The effect of the precision of the spectrophotometric measurements, the purity of the aromatic amine, photochemical decomposition of the amine, and the composition of the fuel on the accuracy of the analysis is discussed and the results of tests of the precision of the procedure are given.

The accuracy of the spectrophotometric method depends upon the purity of a standard sample used for calibration purposes, as well as the extent of contamination of the fuel with other substances which absorb ultraviolet light in the region from 3050 to 2800 A wavelength and which can be extracted from the fuel by aqueous hydrochloric acid along with the amine. The analysis is not affected by the type of hydrocarbon in the gasoline, nor do tetraethyl lead or ethyl-fluid dye in the amounts usually present in aviation fuels interfere. In analyses of typical hydrocarbon and gasoline solutions containing various aromatic amines in concentrations from 0.4 to 1.7 percent by weight, results accurate, on the average, within 1/2 percent of the amine have been obtained.

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Infrared-Spectrophotometric Analysis of Binary and Ternary Mixtures of Liquid Hydrocarbons. By Alden P. Cleaves and Mildred E. Sherrick. NACA WR E-89, 1945. (Supersedes NACA ARR E5F27.) 13 pp.; 3 tables; 5 figs.; Unc.

An investigation was conducted to determine the suitability and precision of a modified, routine-model, infrared spectrophotometer for analyzing binary and ternary mixtures of aircraft-fuel components.

Analyses by means of infrared measurements are described for the following hydrocarbon mixtures: 12 known mixtures of 2,2,3-trimethylbutane (triptane) and cyclohexane, 4 known mixtures of triptane and benzene, and 4 known mixtures of triptane, cyclohexane, and benzene.

The effects of certain factors on the accuracy of the analyses are considered and the precision attained is reported. Computed differences between weighted and spectrophotometric percentages are regarded as uncertainties of the analyses. Five repeated spectrophotometric measurements on the groups of four known mixtures make possible the estimation 2956
of the reproducibility for these cases. Imperfect reproducibility and minor deviations of the measurements from a linear relation between extinction and concentration are important sources of uncertainty.

The results indicate that rapid and reliable analyses of binary and ternary mixtures of the three types of liquid hydrocarbon represented by 2,2,3-trimethylbutane (triptane), cyclohexane, and benzene are feasible by use of a routine-model infrared spectrophotometer with an average uncertainty (relative to compounds regarded as pure) of approximately ±1 percent. The improved reliability that results from determining the mean of five extinctions indicates the desirability of repeating extinction measurements when a small increase of time required for analysis is unimportant.

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<u>The Infrared Spectra of Spiropentane, Methylenecyclobutane and 2-Methyl-1-Butene.</u> By Alden P. Cleaves and Mildred E. Sherrick. NACA TN 1160, 1946. 5 pp.; 1 table; 2 figs.; Unc.

The infrared spectra of spiropentane, methylenecyclobutane, and 2-methyl-1-butene were measured in the region from 3 to 14 microns with a rock-salt prism spectrometer of medium dispersion. The pure samples were prepared at the NACA Cleveland laboratory. The vapors of these three C_5 hydrocarbons were investigated at room temperature and at pressures in the range from 80 to 300 millimeters of mercury absolute in a 10-centimeter cell. The spectra were compared with each other and with Raman data for the same compounds.

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<u>A Spectrophotometric Method for Identification and Estimation of Alkylnaphthalenic-Type Hydrocarbons in Kerosene.</u> By Alden P. Cleaves and Mildred S. Carver. NACA TN 1243, 1947. 11 pp.; 2 tables; 10 figs.; Unc.

A spectrophotometric method for identifying and estimating approximate amounts of naphthalenic-type hydrocarbons, which is suitable for finding differences in the naphthalenic content of kerosene fractions of petroleum, is presented. Comparison of the ultraviolet spectra of several naphthalenic compounds, regarded as typical standards, with the spectra of cuts of a kerosene or with the spectrum of the whole kerosene is the basis for the method. Estimates of the naphthalenic content of the cuts and of the kerosene investigated are included to illustrate the method; possible effects of spectroscopic interference are considered. The spectra of the cuts were found to be very similar to the spectra of the respective naphthalenic compounds chosen as typical.

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Application of an Ultraviolet Spectrophotometric Method to the Estimation of Alkylnaphthalenes in 10 Experimental Jet-Propulsion Fuels. By Alden P. Cleaves and Mildred S. Carver. NACA RM E6K08, 1947. 11 pp.; 1 table; 2 figs.; Unc.

A means of using the strong absorption by alkylnaphthalenes in the range from approximately 2500 to 2700 Å to check estimates of the concentrations based on spectrophotometric measurements at about 3150 A has been devised and applied to 10 experimental jet-propulsion fuels that are petroleum cuts boiling in the range from 100° to 700° F (approximately 40° to 400° C). The 10 fuels investigated are one Yates, three Hastings, two Tomball, two Bradford, and two Midway crude cuts. This check procedure involved empirically determining the average characteristic extinction at 2650 A most suitable for alkylnaphthalenes in these fuels and estimating the amount of other aromatics, which were largely monocyclic. Sums of amounts of alkylnaphthalenes and of other aromatics constituted spectrophotometric estimates for total aromatics. Differences between these estimates and values for total aromatics in the same samples obtained at the Petroleum Experiment Station, Bureau of Mines, Bartlesville, Oklahoma, by a silica-gel adsorption method were recognized to be due to several causes including interfering absorption, erroneous estimates of the amounts of other aromatics, and small inaccuracies of the Bartlesville data. Nevertheless these differences were tentatively attributed entirely to errors in spectrophotometric estimates of alkylnaphthalenes in order to establish an upper value for the order of magnitude of these errors, which was computed to be about 0.2 percent of total sample. In this manner the spectrophotometric method for estimation of alkylnaphthalenes was shown to be more accurate than was formerly expected and some additional information concerning the composition of the fuels was obtained. The possibility of undetectable interference, however, prevents proposal of ultraviolet estimation of total aromatics as an independent method except in particular cases.

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A Method for Determination of Aromatics in 150° to 300° C Fractions of Crude Petroleum by Measurement of Aniline-Point Rise. By Arthur M. Busch, Alden P. Cleaves, and Robert R. Hibbard. NACA TN 1641, 1948. 16 pp.; 4 tables; 4 figs.; Unc.

A method for determining aromatics in 150° to 300° C fractions of crude petroleum is described. Rise in aniline point resulting from the removal of aromatics from synthetic mixtures by percolation through a particular column of silica gel was found to be an almost linear function of the known aromatic content. A general curve for analysis of cuts of crude petroleum having molal average boiling points near 218° C is presented. Modified curves for more accurate analysis of cuts having average boiling points between 150° and 290° C are also included. Results on nine reblends of aromatics extracted from two cuts of different crude petroleums indicated that aromatics having molal average boiling points near 218° C could be determined with an average error of 0.84 percent by volume based on total sample. Analyses of five cuts of four crude petroleums agreed to within an average of 2 percent with analyses of the same samples by a different method at another laboratory.

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Quantitative Analysis of Ternary Mixtures of Naphthalene, 1-Methylnaphthalene, and 2-Methylnaphthalene by Ultraviolet Spectrophotometry. By Alden P. Cleaves, Mildred S. Carver, and Robert R. Hibbard. NACA TN 1608, 1948. 8 pp.; 5 tables; 4 figs.; Unc.

A method for quantitative analysis of ternary mixtures of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene on the basis of ultraviolet absorption in the region from 3000 to 3300 A is presented and the effect of interference by a fourth absorber was investigated. Some data pertinent to possible interference by sulfur compounds of the types expected in petroleum are also included.

Twelve synthetic ternary mixtures of the three naphthalenes were analyzed with an average error of 0.8 percent of the alkylnaphthalenes present.

The method was applied to seven cuts of American crude petroleums that distilled at temperatures which indicated that the three lowest boiling naphthalenes constituted nearly all the condensed dicyclic aromatics present. Accuracy in the case of the cuts of crudes could not be definitely established but was estimated to be about 0.03 percent of the sample.

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Determination of Tetraethyllead in Aviation Gasoline. By Lester Newman, John F. Philip, and Adolph R. Jensen. Anal. Chem., vol. 19, no. 7, July 1947, pp. 451-453.

An iodometric method for the determination of tetraethyllead that is applicable to all aviation gasolines currently used is presented. Briefly, the fuel is shaken with an excess of alcoholic potassium triiodide solution and the excess iodine titrated with sodium thiosulfate, giving a maximum deviation of ±0.05 ml of tetraethyllead per gallon, compared with A.S.T.M. results. Minimization of olefin and amine interferences is described.

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The System Cyclopentane-Neohexane-Aniline. By K. T. Serijan, R. A. Spurs, and L. C. Gibbons. Jour. Am. Chem. Soc., vol. 68, no. 9, Sept. 1946, pp. 1763-1764.

Due to the possibility of purifying commerical cyclopentane by extracting the contaminant, neohexane, with aniline, the ternary system cyclopentane-neohexane-aniline has been investigated experimentally at 25° and 15°. Data for the solubility curves and the composition of conjugate liquids and the phase diagrams are given.

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Carbon-Hydrogen Groups in Hydrocarbons - Characterization by 1.10- to 1.25-Micron Infrared Absorption. By R. R. Hibbard and A. P. Cleaves. Anal. Chem., vol. 21, no. 4, Apr. 1949, pp. 486-492.

The average numbers of primary CH_3, secondary CH_2, and aromatic CH groups in hydrocarbons are determined by absorption spectroscopy in the 1.10 to 1.25 (8000 to 9000 cm^{-1}) near-infrared region. A slightly modified, small glass prism spectrometer is used. Because the amounts of absorption of these functional groups are substantially constant in all hydrocarbons of a given class, calibration with a few members of a class permits the analysis of streams containing any number of components of the same class. Estimates on the amount of chain branching in paraffins and the degree of substitution on naphthene and aromatic rings can be obtained.

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Determination of Carbon-Hydrogen Groups in High Molecular Weight Hydrocarbons by Near-Infrared Absorption. By Albert Evans, R. R. Hibbard, and A. S. Powell. Anal. Chem., vol. 23, no. 11, Nov. 1951, pp. 1604-1610.

The amounts of absorption of methyl (CH_3), methylene (CH_2), and aromatic CH groups in the 1.10 to 1.25 micron near infrared region are shown to remain substantially constant in hydrocarbons of 34 carbon atoms or less. Analysis can be made for the average numbers of these groups in mixtures after calibrating with a few pure compounds. A new method of correction for the anomalous behavior of naphthenes is presented.

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Determination of Aromatics and Olefins in Wide-Boiling Petroleum Fractions. By A. E. Spakowski, A. Evans, and R. R. Hibbard. NACA RM E50D03, 1950. 10 pp.; 4 tables; 1 fig.; Unc.

A method is described for the determination of aromatics and olefins in petroleum fractions with wide-boiling ranges by a combination of sulfonation, chromatography, and specific dispersion. Chromatography is used to separate the sample into a pure nonaromatic, an intermediate, and a pure aromatic fraction. Total aromatics are found as the sum of the pure aromatic fraction and the volume of aromatics in the intermediate fraction as determined by specific dispersion. Sulfonation yields the percentage of olefins plus aromatics and the percentage of olefins is determined by difference. Less than 8 hours are required per analysis. The method has been checked on blends of pure hydrocarbons and has been found to yield inaccuracies of less than 1 percent in the determination of olefins and aromatics.

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